Quadpack X-Band T/R Module for Active Phased Array Radar

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ABSTRACT

A four-element Transmit/Receive Module (Quadpack) design is presented, with two independent receive channels per element for application in the X-band Active Phase Array Radar. This wideband T/R Module features typical output powers of 8W pulsed and 5W CW, typical 5 dB Noise Figure with six-bit amplitude and phase control. The CW-mode of operation enables missile illumination and guidance. Sophisticated packaging together with appropriate MMIC technologies resulted in a high yielding and high performance T/R Module, of which more than 1000 Quadpacks (4000 elements) have been manufactured to date.

INTRODUCTION

The T/R Module (Figure 1), which is described here, is the main antenna part in the X-band Active Phased Array Radar (APAR), the latest generation Multi-Function Radar System. APAR is realised as a combined development for the Canadian, Netherlands and German Navies, by companies from the three participating countries, with Signaal as main contractor.

APAR is intended to be used for horizon search and air target tracking as well as back-up volume search. Moreover it has a guidance capability for most modern semi-active homing missiles (CW illumination). The system uses four antenna faces (360 degrees azimuth coverage), each consisting of over 3000 wave guide radiators, every one of which is connected to its own T/R element. The T/R Module is an assembly of four of these elements.

Within the Antenna structure, the Quadpacks are mounted to carrier plates, providing mechanical support and liquid cooled heat sink. Slide-on connectors are used for the RF connections with the beam-forming networks and with the radiators. Control data and power supply lines are connected to a PCB, which is part of the T/R Module.

T/R MODULE ARCHITECTURE

The T/R Module is an assembly of four electrically identical T/R elements. The active RF functions are realised by GaAs MMICs. See Figure 2 for a block diagram. A High Power Amplifier (HPA) follows the Driver Amplifier (DRA), to generate the required level of transmit power, to be fed to the radiator. The Low Noise Amplifier (LNA) has two outputs, feeding two receive channels each with a 6-bit Phase Shifter (PHS) and a (6+2)-bit Variable Gain Amplifier (VGA), to allow for independent phase and amplitude adjustment. Three additional SPDT MMIC Switches (SW) permit to use one set of PHS and VGA for both the receive and transmit signal. A reflective Limiter (LIM) in front of the LNA accomplishes the protection of the LNA. The HPA is protected from high power levels reflected by the limiter, using a 4-port Circulator (CIRC), which also functions as a T/R switch. Two silicon ASICs are used to convert the serial input data to parallel output signals, for controlling the PHS and VGA in each channel.

MMICs determining the radar's range performance (LNA and HPA) are implemented in high performance PHEMT processes, while the other MMICs are designed in a relatively inexpensive MESFET process.

A T/R Module with two independent receive channels circumvents the difficulties in achieving the correct antenna tapering as well as tracking between the channels, required for proper monopulse operation [1]. This configuration has the advantage of simplified design of the beamforming networks, because amplitude and phase errors can be corrected by the independent PHS and VGA.

The radar application demands large scan-angles without the occurrence of grating lobes, restricting the maximum spacing between the radiating elements ($< 0.5\lambda$). This mechanical constraint requires a high level of miniaturisation and multilayer packaging. In addition, using two independent receive channels requires stringent crosstalk control, which is accomplished by dedicated package design.

MMIC CHIPSET

The T/R Module incorporates MMICs manufactured in North America and in Europe.

The LNA features a typical noise figure of less than 2.0 dB across the band and dual isolated outputs. The 5.7 mm^2 chip is implemented in 0.25 µm PHEMT technology.

The VGA, PHS and SW are all fabricated in a special version of Nortel's inexpensive 0.8 µm low-noise MESFET process, which has been optimised for minimum gate-lag and drain-lag effects [2]. This allows for the rapid settling of RF parameters following the switching of control settings.

The 6 mm^2, 6+2-bit VGA was designed by TNO-FEL, The Hague, The Netherlands. Six of the bits control a highly linear 64-step gain ramp as shown in Figure 3. The remaining 2 bits provide four independent steps of coarse adjustment to compensate for gain variations throughout the receive channel. Both gain controls use multi-segment dual-gate FETs as the control elements in active gain stages with a dynamic range exceeding 30 dB.

The 6-bit PHS was designed by DASA, Ulm, Germany. The achieved phase control is shown in Figure 4. The 8.1 mm^2 chip is based on switched high-pass and low-pass filters resulting in low amplitude variation versus phase setting.

The SW, also designed by DASA, re-routes the RF signal between receive and transmit modes. The chip is 1.7 mm^2 in area.

The DRA used in the transmit path has an output power capability of 27 dBm, was designed by Signaal, and is implemented in a high power variant of the Nortel MESFET process. The 8.75 mm^2 chip is 4-stage design.

The HPA is a commercially available design. Capable of exceeding 9 W pulsed, the 13 mm^2 chip is implemented in 0.25 µm PHEMT technology. A notable feature of this part is the excellent spurious-free and subharmonic-free performance.

PACKAGING TECHNOLOGY

The T/R Module enclosure consists of a machined chassis and lid. Although this enclosure is not strictly hermetic, together with the use of hermetic ceramic packaging, it provides full environmental protection.

The module chassis contains four channels, which house the four Transmit/Receive elements. The internal walls separate the individual channels and provide crosstalk control. The module chassis also functions as the heat sink. RF input / output is done through coaxial connectors located in the sidewalls of the module chassis. The power supply and control signal distribution is provided by PCB that is common to all four elements. This PCB is located above the multilayer ceramic packages.

Each of the four identical T/R elements consists of four fully hermetic ceramic packages and a 4-port circulator. The ceramic packages house the individual MMICs and provide the interconnect for RF signal and power supply and control signal. RF connections between individual packages and the circulator are accomplished through wire bonding. The pins in the individual ceramic packages are used to connect the packages to the PCB.

Careful circuit partitioning has been done to optimize the assembly yields at the individual package level. Figure 5 shows one of the four packages. This particular package contains both, Transmit (Driver Amplifier) and Receive (Low Noise Amplifier) circuitry. These are located in two individual cavities for maximum signal separation.

Multilayer cofired ceramic technology (MLCC) was used for the MMIC packaging due to its high interconnect density, excellent line impedance control, high thermal conductivity, inherent hermeticity, and design flexibility. Figure 5 shows the package over view and cross-section.

SERIES MANUFACTURING

MMIC fabrication follows Nortel's standard process flows for both Low Noise and Power Processes. Wafer thinning and through wafer via formation (SVIA) are conducted as a separate back end operation. Process Control Monitor criteria are used to qualify a wafer to pass from Fabrication to SVIA and then on to Data and Device Integrity Manufacturing (DDI) where wafer probe, dicing and visual inspection steps are performed. The output of the DDI area is known good MMICs for the Assembly and Test processes.

T/R Module manufacturing is based on Nortel's expertise in producing complex multi-chip modules and assemblies. This expertise has been used during the T/R module design in general, and during component and material selection in particular. The suppliers of module components have been selected on the basis of process capability. Critical parameters are sampled and reported by component suppliers on each batch of components. These measurements are entered into a materials database, and the quality of incoming components can be easily monitored by viewing the chronological graphs of critical parameters. Using this approach, the components are procured in a ship-to-stock manner which reduces the total module cost.

Statistical tolerance analysis has been used to ensure minimum variability in module performance. Special algorithm has been developed for the automated placement of individual packages into module chassis. This algorithm combined with the precise and repeatable position of pattern in the packages ensures highly consistent wire-bond length.

The assembly equipment set has been selected based on the projected T/R Module volumes and the target product cost. A significant process development and optimization program has been implemented and is currently 85% completed. MMIC die are eutectic or epoxy die attached with automated systems at the package level. All purchased engineered materials are manufactured to stringent process control and acceptance criteria to ensure-to-stock quality assurance. After hermetic sealing of the subassembly packages, tests of hermeticity and electrical performance are conducted. Successfully passing packages are inventoried for final T/R Module Assembly.

The T/R Module functional test strategy has been developed with the view of lowest module cost. Each MMIC, RF package, and finally module undergoes full functional test to ensure that the test dropouts occur at the lowest level of integration. All of the functional testing is performed using a custom developed fully automated RF test system. A typical 100% RF functional test takes approximately 7 minutes and covers roughly 3500 data samples at various frequency, power, and module settings. The test results are stored in a secure database for further access and analysis. The repeatability of each parameter is analyzed, and the analysis results are used for optimizing the test coverage at each subassembly level.

ELECTRICAL PERFORMANCE

At the module level the automated RF tester performs a full suite of RF tests on each of the T/R Module's twelve RF ports as well as testing the module's DC functionality for power supply and control. All tests are conducted using the same temperature controlled fixture.

Each of the T/R Module's four elements is designed and built in an identical configuration. The integrity of this design can be seen in the test results shown below which illustrate the tightly correlated performance between elements. Of specific note are the following parameters:

- Typical Pulsed Output Power exceeds 37.5 dBm (Figure 6).
- Noise Figure typically better than 6.0 dB (Figure 7).
- Small Signal gain in excess of 30 dB with more than 30 dB of dynamic range (Figure 8).
- Cross-talk levels of 40 dBc between adjacent T/R Elements.

CONCLUSION

The multi-nation development of high technology which utilize the strengths of all participants is a reality for the design of Quadpack T/R Modules. The participants have demonstrated a high performance X-band Quadpack T/R Module for use in anti-air warfare applications, that is economical to manufacture and test in production volume.

ACKNOWLEDGEMENT

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The authors would like to thank specifically the MMIC design groups at Daimler-Benz Aerospace, Germany for their design work done on the PHS and SW MMIC's and TNO-FEL, The Netherlands, for the VGA MMIC.

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FIGURES

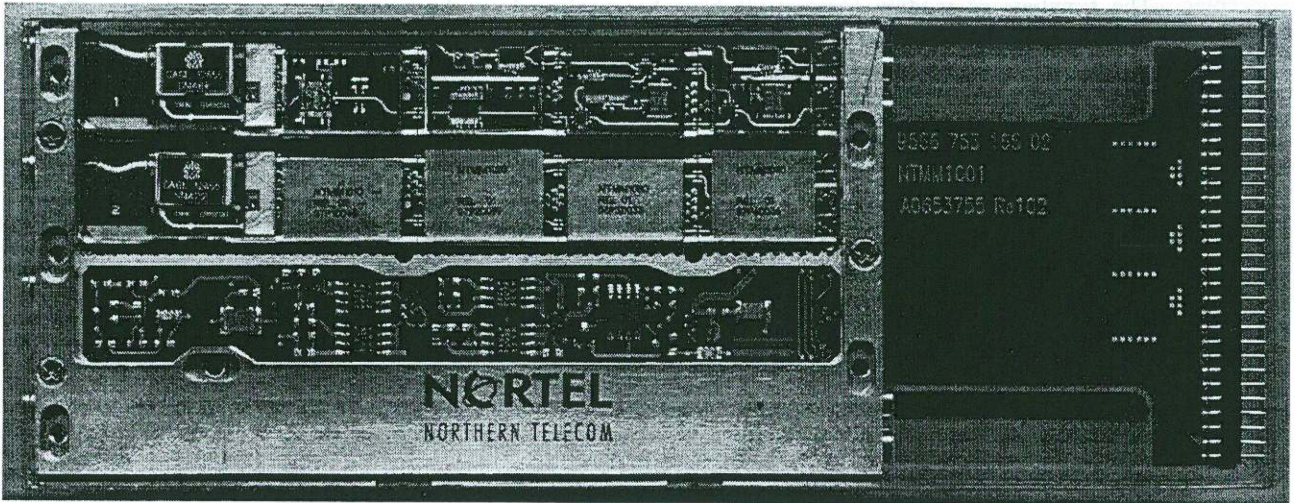

Figure 1 APAR T/R Module

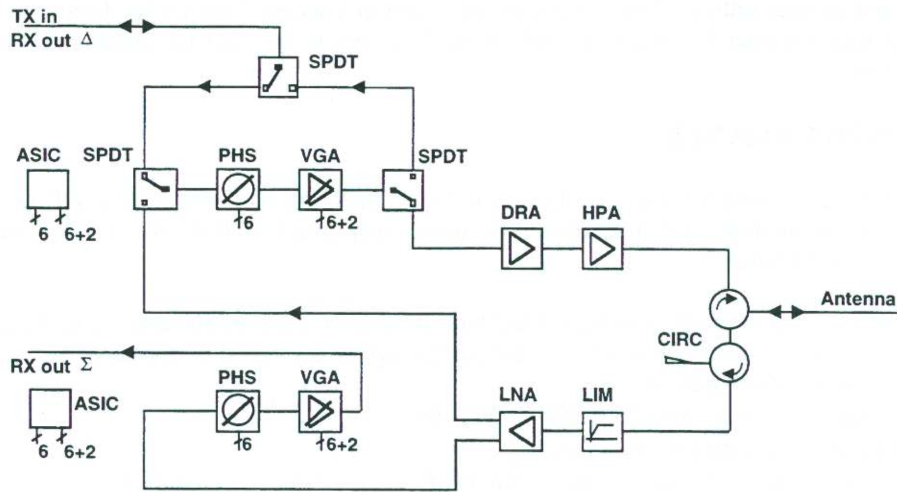

Figure 2 T/R Element block diagram

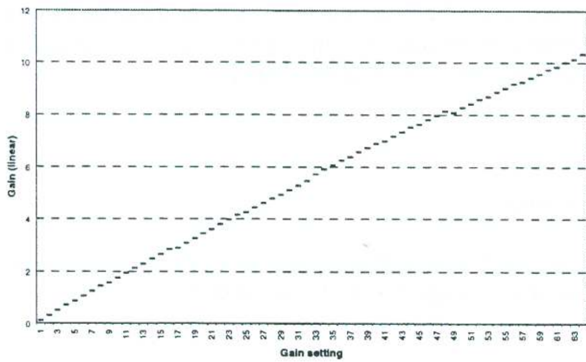

Figure 3 VGA 6-bit performance

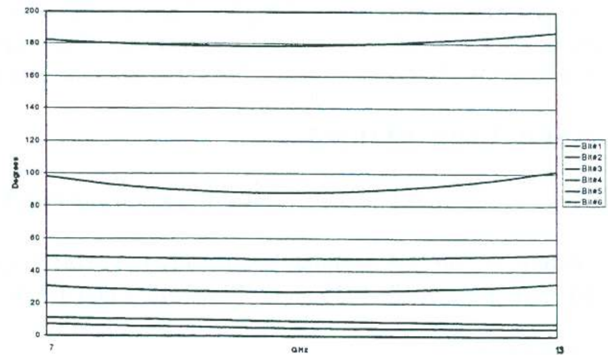

Figure 4 PHS 6-bit performance

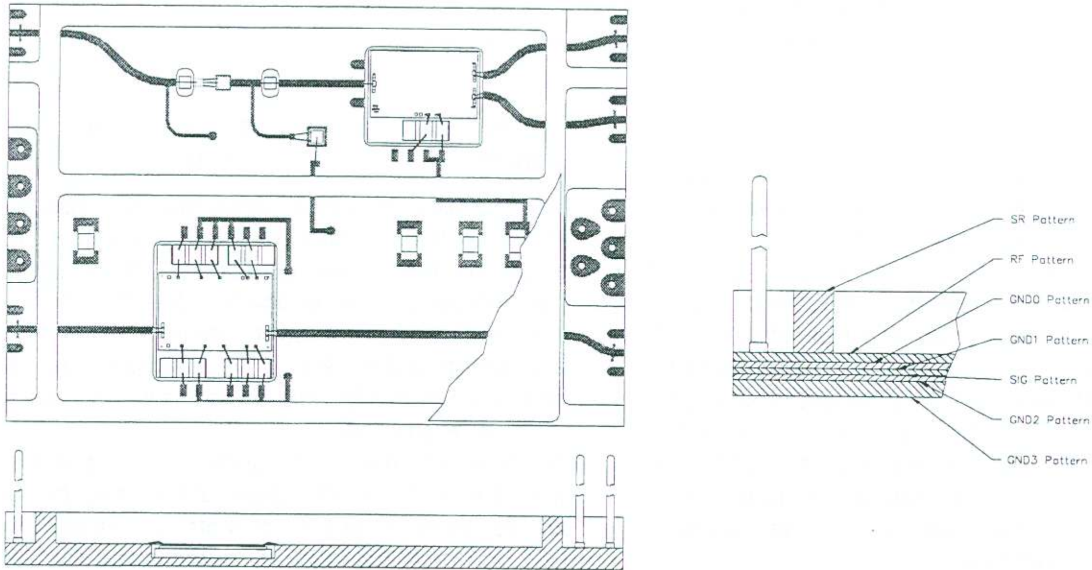

Figure 5 Multilayer Ceramic Package

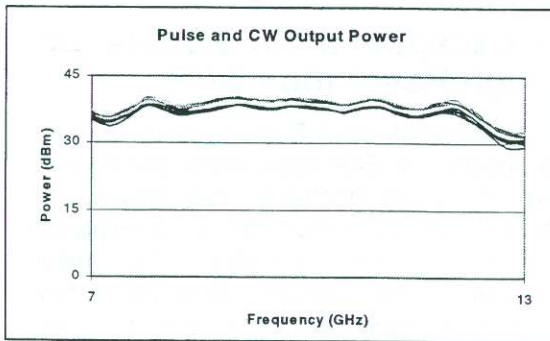

Figure 6 Output Power CW and Pulsed Mode

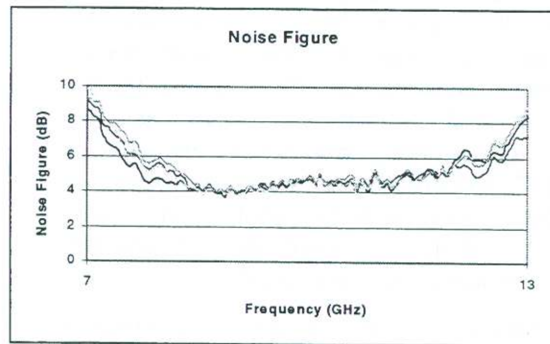

Figure 7 Noise Figure

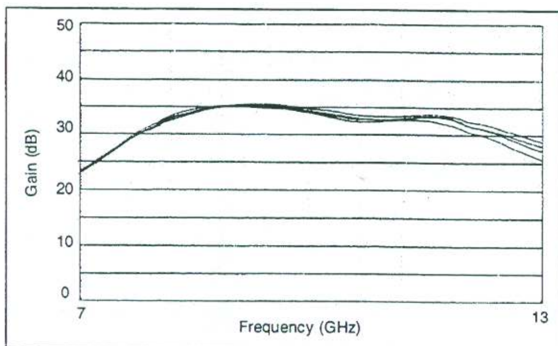

Figure 8 Small Signal Gain Sigma Channel