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HIGH-SPEED ADC AND DAC MODULES WITH FIBRE OPTIC INTERCONNECTIONS FOR TELECOM SATELLITES

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ABSTRACT

The flexibility required for future telecom payloads calls for the introduction of more and more digital processing capabilities. Aggregate data throughputs of several Tbps will have to be handled on-board, thus creating the need for effective, ADC-DSP and DAC-DSP high-speed links. ADC and DAC modules with optical interconnections is an attractive option as it can solve easily the transmission and routing of the expected huge amount of data. This technique will enable to increase the bandwidth and/or the number of beams/channels to be treated, or to support advanced digital processing architectures including beam forming.

We realised electro-optic ADC and DAC modules containing an 8 bit, 2 GSa/s A/D converter and a 12 bit, 2 GSa/s D/A converter. The 4-channel parallel fibre optic link employs 850-nm VCSELs and GaAs PIN photodiodes coupled to 50/125-µm fibre ribbon cable. ADC-DSP and DSP-DAC links both have an aggregate data rate of 25 Gbps. The paper presents the current status of this development.

1. MODERN TELECOM PAYLOADS

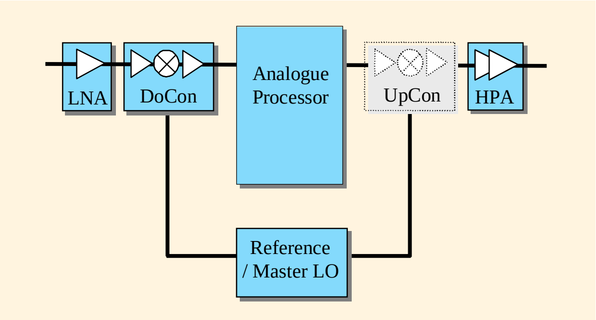
In the satellite telecommunication sector, operators have to face a number of new challenges. In order to cope with depleting resources in orbital positions, they turn towards increasing capacity payloads, with higher number of beams and larger aggregate bandwidth. This trend is concurrently fuelled by the demand for provision of broadband multimedia services.

Operators are anticipating the emergence of a new market based on broadband communications via satellite in the next five to ten years, provided that satellite services are cost-effective and flexible. In this perspective, they expect from future broadband space systems that they offer high data rate connections to very large numbers of low-cost terminals. Only satellites with very large capacity will enable to achieve affordable communication prices. Another major challenge consists of meeting the evolution of needs over the average 15 years of a satellite lifetime. This definitely calls for flexible and transparent payload solutions, which are independent of the air interface.

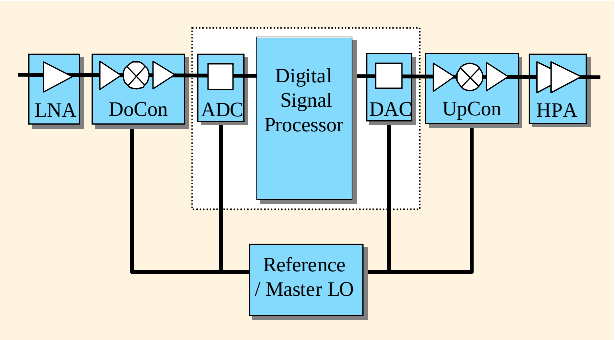
New satellite payloads need to be designed so as to meet such requirements of larger bandwidth, system transparency and flexibility. Several technical options are being pursued [1] but in any case, broadband payloads will feature complex multi-beam active antennas, hundreds of channels to receive, route and transmit. Fig. 1 illustrates the main approaches to future payload architectures. Communication payloads are moving from pure bent-pipe repeaters to more advanced analog sub-systems or fully digital processor-based solutions.

In these conditions, payloads will likely incorporate an increasing amount of digital signal processing (DSP) equipment for filtering, switching and/or regenerating telecom signals. Digital transparent processors (DTP) are one example of such advanced telecom repeater sub-systems. They have analog-to-digital (ADC) and digital-to-analog converters (DAC) respectively on their input and output accesses and make use of digital processing in order to provide flexible beam-to-beam connectivity and variable bandwidth allocation. DTPs are particularly well-suited for routing channels or sub-channels with fine bandwidth granularity in telecom missions with multiple-beam antenna coverage, and offer reconfiguration flexibility when mission reorientation is needed.

DTPs with additional digital beam-forming (DBF) functionality will collect and handle digital samples of the electromagnetic waves from many antenna array elements. By combining these samples with appropriate weightings, they enable to form multiple contemporaneous beams, and/or to control the beam shape and side-lobe levels. DBF concept is particularly attractive for telecom missions calling for reconfigurable multiple-beam antenna coverage. It may also find application in next generation SAR (synthetic aperture radar) as the antenna pattern could be dynamically controlled to implement various scanning modes, or to reduce the effect of directional jammers.



(a) analog transparent telecom payload



(b) digital processor-based telecom payload

Fig. 1. Modern telecom payload architectures.

Fig. 2 shows a schematic of an advanced receiver antenna based on DBF. Such architectures feature a large number of A/D conversions and high-speed links from the ADCs to the central processor; namely, there would be as many ADCs as antenna receiver elements. High-speed digital processors with or without DBF are expected to be widely spread in future telecom repeaters and thus a technology breakthrough is required to support the expected huge amounts of data.

Fig. 3 gives the aggregate throughput required for interconnections in future DTPs, which can reach the 1 Tbps range. This requirement is extended to a few Tbps when DBF functionality is included. For instance, most ambitious projections look at payloads featuring 200 beams with up to 1 GHz bandwidth per beam. If a fully digital processing approach is adopted, this may require 200 ADC-DSP and DSP-DAC links with data rates up to 25 Gbps each (equals to digitising a 1 GHz signal at the Nyquist rate with 10 bits/sample plus extra coding), resulting in a total throughput of up to 10 Tbps.

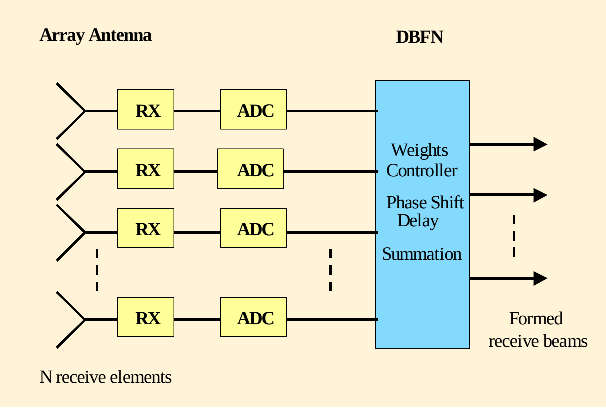


Fig. 2. Schematic of digital beam forming.

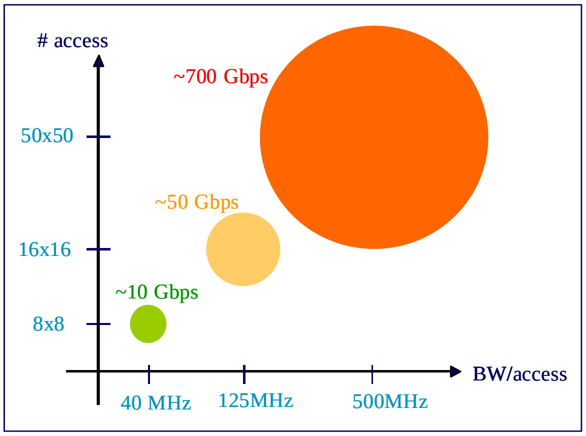


Fig. 3. Aggregate throughput demand for future DTP.

In summary, high-speed digital signal processing is expected to be widely spread in future telecom repeaters and antenna beam-forming networks. In this perspective, we have undertaken to assess the benefits and constraints of optical interconnections [2] as a communication technology for supporting the huge amounts of data expected in future digital processor-based payloads. In particular, ADC and DAC modules with fibre optic interfaces are of outmost interest. With very substantial savings in mass and volume, this will effectively support the bandwidth required to the ADC-DSP and DSP-DAC high-speed links while removing any distance limitation, and better preserving signal integrity. This in turn adds some flexibility in the design and partitioning of the equipment. It enables to split the ADC and DAC modules from the processor, and for instance to shift the ADC and DAC modules as close as possible to the antenna elements.

2. FIBRE OPTIC LINK ALTERNATIVES

2.1 Link architectures

There are three basic options to realise a fibre optic interconnection with 25 Gbps transmission speed: parallel fibre link, serial link using wavelength division multiplexing (WDM) and serial link without WDM. Parallel fibre optic link means that the aggregate bit-stream is transmitted through parallel optical channels using multifibre cable, Fig. 1. Multiplexing is not necessary neither in electrical nor in optical domain and all parallel channels can use the same optical wavelength. DC-balancing, e.g. with 8b/10b coding, is required for optical links. The 25 Gbps system can be implemented with 12 channels operating at 2.083 Gbps, 8 channels at 3.125 Gbps or 4 channels at 6.25 Gbps. This baud range is compatible with the high-speed interfaces of FPGA circuits currently on the market.

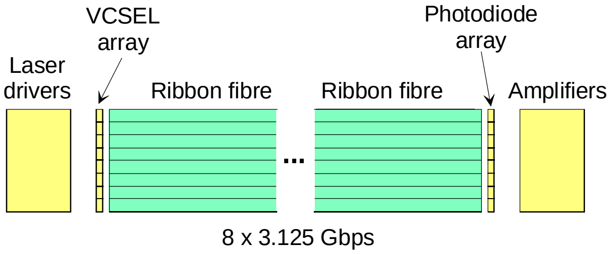


Fig. 1. Parallel fibre optic link using VCSEL and photodiode arrays with multifibre ribbon cable.

Serial links use a single optical fibre. Coarse wavelength division multiplexing (CWDM) is employed in short distance communications, Fig. 2. It is characterized by wider channel spacing than the more common dense WDM (DWDM) technology that is used in long-haul and high-capacity systems. The central wavelengths of CWDM are specified in 20 nm spacing between 1270 … 1610 nm [3]. CWDM systems usually contain separate passive optical modules that perform multiplexing and demultiplexing functions.

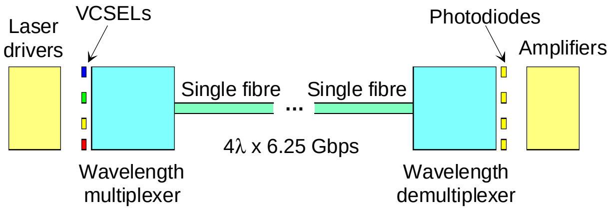


Fig. 2. Serial fibre optic link using CWDM with VCSELs and photodiodes.

Compared to DWDM, CWDM systems can produce more cost-effective solutions, thanks to a combination of uncooled lasers, relaxed laser wavelength selection tolerances and wide pass-band filters. Commercial applications typically use single-mode technology, but CWDM can be applied with multimode fibres.

The third option is to electronically serialise data into a single 25 Gbps stream and transmit it through a single fibre, Fig. 3. So far, direct modulation of lasers has not been commercially applied at such a high data rates. Therefore, the transmitter must be implemented by the use of continuous-wave laser and an external optical modulator based on electro-optic or electro-absorption effect. In the future, it might be possible to realise short reach serial links operating at 25 Gbps based on directly modulated vertical cavity surface emitting lasers (VCSELs) [4].

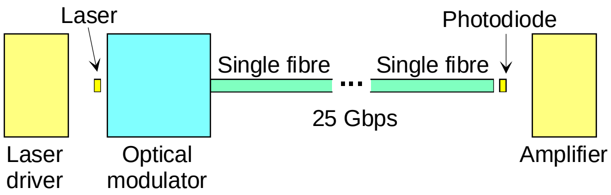


Fig.3. Serial fibre optic link using continuous-wave laser with external optical modulator.

One disadvantage of fully serial transmission is the high-bandwidth electronics required for the serialiser/deserialiser circuitry, modulator driver and amplifiers. Such electronics has high power consumption and requires significant amount of board area. In addition, the receiver sensitivity is quite poor at 25 Gbps, resulting in low optical loss budget. Another problem is the coding of the original data to a single 25 Gbps signal. There are no FPGA circuits supporting such high I/O rates and commercially available multiplexers/demultiplexers are specified mainly for standard SDH/SONET rates. Proprietary circuits without the FPGA flexibility should be developed.

2.2 Light emitters and transmitter electronics

The light emitting device converts electrical signals into the light output that can be injected into the optical fibre. There are two types of semiconductor emitters, namely light emitting diodes (LED) and laser diodes (LD), that are suitable for high-speed data transmission. LED-based transmitters are commercially available up to 622 Mbps and high-speed modulation of LEDs has been demonstrated only up to 1.7 Gbps. Therefore LEDs are not suitable for the ADC - DSP system due to their limited speed and poor fibre coupling efficiency leading to a low signal-to-noise ratio at the receiver end.

Laser diodes can be divided into Fabry-Perot (FP), distributed feedback (DFB), distributed Bragg reflector (DBR) and VCSELs. DFB lasers are typically used in high-speed long-range transmission networks. Due to their more complicated internal structure, DBR and DFB lasers are more expensive than FP devices. In addition, active temperature control is required to maintain the lasing wavelength. Because the link length requirement of the ADC - DSP system is only a few tens of meters, there is no need to use either DFB or DBR lasers.

The Fabry-Perot diode laser has been commonly used in fibre optic transmitters and it is available for 850, 980, 1310 and 1550 nm. FP lasers with up to 10 Gbps direct modulation rates can be purchased in dies, on different subassemblies or as packaged devices. 1300-nm FP lasers are planned to be used in fibre optic harness in the ESA SMOS satellite [5]. Parallel fibre optic connections would require the use of separate FP laser chips, as there are no linear arrays available. This would increase the circuit board area and complicate the assembly of the electronics.

VCSELs and multimode fibres are widely used in local and storage area networks. VCSEL technology offers low threshold current (and hence low power consumption), high speed, and ease of packaging. VCSELs also have a lower temperature dependence of the threshold current than other lasers, so they can work in a wider temperature range without temperature control. VCSELs emit a low divergence circular output beam that is easy to couple into the optical fibre. Commercially available VCSEL chips are in practice limited to 850 nm.

10 Gbps optical transmitters using 850-nm VCSELs and PIN photodetectors enable data transmission over 300 m using 50-µm graded-index multimode fibre. 10 Gbps links are more difficult to realise than slower systems due to more demanding high-speed electronics and more stringent packaging requirements. Higher speed results in lower receiver sensitivity and thus smaller link budget. Also the component assortment is more limited at 10 Gbps.

There is a trade-off between the number of channels and their speed. Power consumption of the VCSEL driver circuits is typically 100 mW per channel up to 5 Gbps, whereas 10 Gbps drivers consume 130 mW per channel. On the other hand, as the speed of the individual channel increases, reliability gets worse, as the link budget becomes more stringent with the increasing receiver noise bandwidth and decreasing timing margin. Some redundancy is also lost as loss of one channel causes a greater deficit in the total link capacity.

A 4 × 6.25 Gbps link implemented with 10 Gbps VCSELs and drivers is the optimum in the trade-off between the power dissipation and reliability. The transmitter still has a good timing and jitter margins compared to higher speed systems, and the power consumption is only a half compared to 8 or 12 channel systems operating at lower speed.

Consideration of the radiation hardness of optical fibres and detectors favours the use of light sources working at 1310-nm or 1550-nm windows. Because radiation-induced attenuation (RIA) bands in fibres are centred in the ultraviolet, fibres have better radiation resistance at longer wavelengths [6]. However, the radiation-hardness of laser-optimised 50-µm graded-index fibres was recently tested in the ESA's SpaceFibre project [7]. When considering the typical, fairly low dose rates encountered in space the RIA of a 100-m long link was extrapolated to be between 0.05 and 1. Considering the transmission distances between the ADC/DAC and the on-board DSP (expected less than 10m), the RIA in fibres seems to be very low also at 850 nm.

The reported radiation induced effects in VCSELs have been so small that 850-nm VCSELs are expected to perform well in the foreseeable space missions [8]. A formal qualification process to qualify VCSELs is foreseen by ESA. Because VCSELs also offer small power consumption, they were selected for the parallel link light source. 4-channel 10 Gbps VCSEL arrays and drivers are available as bare dies, which enables the realisation of compact and high-performance fibre optic transmitters.

CWDM systems are typically implemented using edge-emitting FP or DFB laser diodes. They cannot be well integrated as monolithic arrays, and multi-wavelength arrays are not available. Thus, CWDM transmitters are typically single channel devices with fixed wavelength.

There are publications discussing the research results of long-wavelength (1200 ... 1600 nm) VCSELs that might have potential to be used in WDM systems, and some of these have recently been commercialised. However, the availability of long-wavelength VCSELs as bare dies is very limited.

2.3 Photodetectors and receiver electronics

Three photodetector types have potential for fast fibre optic data receivers, namely PIN diodes, avalanche photodiodes (APD), and metal-semiconductor-metal (MSM) diodes. PIN diodes are the most common type in short-reach fibre optic links. APDs are used more in long-distance communications for weak signal detection. MSM diodes are still uncommon in data links possibly due to the technical problems encountered in reducing the high dark current and slow response of photo-generated holes. In high-speed communication, III-V semiconductor-based materials, especially GaAs and InGaAs, are most popular.

Silicon detectors are also possible at wavelengths below 1 µm, but they are rarely used. Because of the thicker depletion region, Si PIN photodiodes are much more sensitive to single event upsets (SEU) than GaAs detectors and are not suited for use in radiation rich environments [9], [10]. Therefore the use of GaAs PIN diodes seems to be the best option for the DAC module photodetector. 4-channel 10 Gbps GaAs and InGaAs photodiodes and receiver amplifiers are available as bare chips.

2.4 Fibre cables and connectors

Parallel fibre optic links need multifibre cables and connectors. Telecom applications use acrylate-encapsulated and edge-bonded ribbon cables. When compared to these telecom-grade products, GORE™ Mil-Aero Fiber Optic Ribbon Cables offer improvements in operating temperature range (–55 … +125 °C), minimum bend radius (12.7 mm), chemical resistance, and overall ruggedness without compromising size or flexibility [11]. Both single-mode and multimode ribbons are supplied with standard fibre counts of 4 and 12. Non-ruggedised 4-fibre ribbon cables suitable for intra-box connections weigh 1 g/m. Ruggedised cables with Kevlar strength members for inter-box links have a mass of ca. 10 g/m. For comparison, ruggedised 1.8-mm simplex fibre cables weigh 4 g/m.

At the moment there are no space-qualified ribbon fibre cables available. Gore’s ribbon cables are starting to be evaluated for use in space applications. NASA has carried out vibration, thermal vacuum and radiation tests for multifibre cables with standard MT-ferrule-based MTP connectors. Test results showed that such assemblies are able to withstand space flight environments used for this characterization [12], [13]. MTP connector with the strain relief weighs 3.5 g. For comparison, Diamond AVIM single fibre connector weighs 6 g.

2.5 Multilayer ceramic circuit boards

Depending on the application, many different substrate technologies are used in hybrid module packaging. Organic boards, such as the epoxy laminates, are favoured in commercial datacom and other lower cost applications. In telecom and harsh environment applications with high reliability and stability requirements, ceramic substrates are commonly used.

Photonic devices and electrical circuits can be hybrid integrated into a wiring board by the use of low temperature co-fired ceramic (LTCC) process. LTCC technology was developed in the 1970’s and 1980's for the extension of thick film hybrid technology [14]. It uses conventional screen printing technique for the conductor patterning on unfired glass-ceramic tape sheets, which are further laminated and co-fired to make a high-density multilayer structure. Today, LTCC modules are employed in automotive and telecommunication applications, such as Bluetooth and cell phone modules.

Low conductor resistance and dielectric loss, multilayer structures with fine-line capability and compatibility with hermetic sealing make LTCC a useful technology for high-speed data transfer applications. In addition, the fair match of the thermal expansion coefficient to optoelectronic chips reduces packaging-induced thermomechanical stresses.

LTCC materials have fairly poor thermal conductivity (about 3 W/mK), but it can be increased by using thermal vias. The precision three-dimensional structures, such as cavities and holes manufactured in the ceramic parts, ease the packaging process via the passive assembly. Because of its inherent advantages in high-speed electronics, possibility to use bare semiconductors chips, low outgassing properties and compatibility with hermetic sealing, LTCC was chosen for the ADC and DAC module circuit boards.

2.6 Selected link options

We decided to design and implement two types of high-speed fibre optic interconnections for the ADC and DAC modules. The principal configuration is the 4 × 6.25 Gbps parallel link employing 50/125-µm graded-index fibres together with 850-nm VCSELs and GaAs PIN photodiodes. The advantages of the parallel link is the availability of the optoelectronic components as bare dies, the proven technology with good reliability and the readiness for scalability either by increasing the transmission speed of each channel or the number of optical channels.

In addition, we decided to test CWDM using 1550-nm band VCSELs, 50/125-µm graded-index fibres and InGaAs photodiodes. The presence of the passive wavelength multiplexer/demultiplexer increases the mass and volume of the device. However, the CWDM approach allows the use of commercially available reliable single fibre connectors, such as Diamond AVIM. Single fibre connectors are in principle easier to handle saving time and effort during the Assembly, Integration and Test phases of building the spacecraft.

The most critical issue in this option is the availability of long-wavelength VCSELs.

3. MODULE DESIGN AND REALISATION

3.1 Module design

The electro-optic ADC module is schematically shown in Fig. 4. The 8 bit, 2 GSa/s A/D converter (National Semiconductor ADC08D1000VIYB) is packaged into an industrial grade low profile quad flat pack (LQFP) having dimensions of 1.4 × 20 × 20 mm^3. The field programmable gate array, FPGA (Xilinx Virtex-4 XC4VFX40) chip sits in a commercial grade ball grid array (BGA) package that has dimensions of 2.7 × 27 × 27 mm^3. These components are not available as bare dies. The optical subassembly (OSA) contains two 4-channel VCSEL arrays (Ulm Photonics ULM850-10-TT-N0104U) and their drivers (Helix HXT3104A) as bare chips. For future scalability and redundancy at the optical communications level we implemented 2 × 4 channels, of which the other half is not operational.

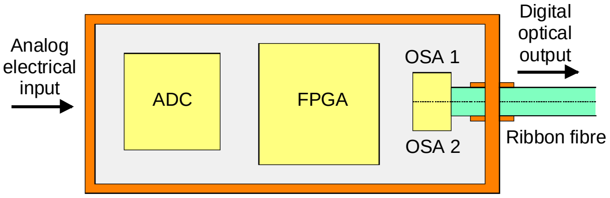


Fig.4. Overview of the ADC module.

The design of the DAC module is similar to its ADC counterpart, Fig. 5. 4-channel photodiode (Albis Optoelectronics PDCA04-70-GS) arrays and receivers (Helix HXR3104A) were purchased as bare dies. The 12 bit, 2 GSa/s D/A converter (Euvis MD653D) is packaged in 128-pin thin quad flat pack (TQFP), whose size is 1.4 × 14 × 14 mm^3. Also here we implemented 2 × 4 channels for future scalability and redundancy.

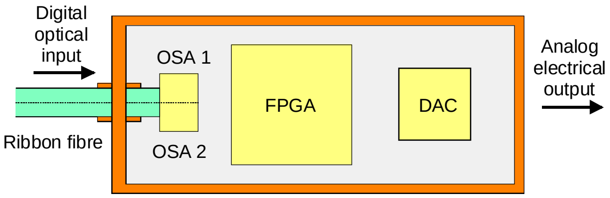


Fig.5. Overview of the DAC module.

3.2 Module realisation

Three samples of different ribbon fibre cable provided by Gore were tested in a thermal-vacuum chamber for 48 hours. Two cables passed the test showing no visible delamination. The more flexible one (Gore FON1214/4/8) was selected for the modules and connectorised with an MT ferrule (US Connect MTF-8MM7-02).

Both ADC and DAC module electronics was manufactured on multilayer ceramic substrates and it consists of two circuit boards: the mother board and the optical subassembly, Fig. 6. The 10-layer mother board contains the A/D converter and the FPGA device and it also serves as the module base plate. OSA consists of the laser drivers, VCSELs and the fibre-coupling structure. The ribbon fibre feed-through was made to the metal frame that was soldered to the mother board. We have used similar structure in the SpaceFibre transceivers that have passed thermal cycling, mechanical shock and vibration testing [15].

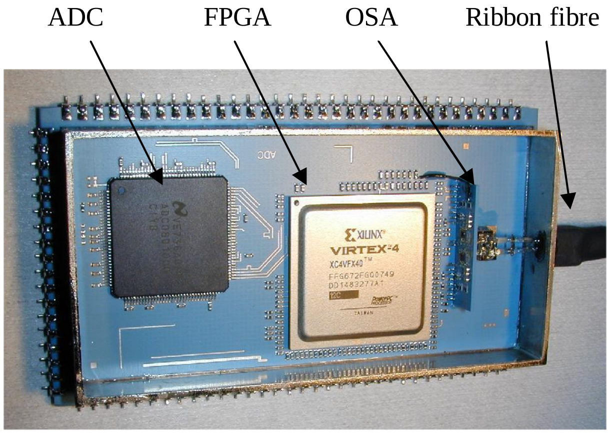


Fig.6. Electro-optic ADC module with 8-channel parallel fibre optic interconnections. Module dimensions are 12 × 50× 90 mm^3 and the mass with connectorised fibre pigtail is 52 g.

4. DISCUSSION

At this moment the electro-optic ADC and DAC modules with parallel fibre optic interconnections are manufactured and their operational testing has been started. The modules using CWDM are under construction. The key functional parameters of the ADC and DAC modules using parallel fibre optics are compared to the end user requirements in Table I. Here the module mass includes a 1-m long ribbon fibre pigtail with MT ferrule.

We see that all the other targets are obtained except the electrical power consumption. However, this is caused by the high consumption of the commercial A/D (1.6 W) and D/A (3.2 W) converters and FPGA (3.5 W) devices. The optical communication consumes only 0.5 W (transmitter) and 0.6 W (receiver) leading to

20 mW/Gbps power efficiency for transmission and 24 mW/Gbps for reception.

ESA's current developments target 1.5 GSa/s, 10 bit A/D converters having a power consumption of 1 W and 1.5 GSa/s, 12 bit D/A converters consuming only 0.6 W. Along the same line of development ESA targets development of ASIC technology with 6.25 Gbps serial links and low power consumption.

Table I. End user requirements vs. module realisation.

Parameter	Requirement	Realisation
Data rate (Gbps)	25	4×6.25
Hybrid module power consumption (W)	< 2	ADC: 5.6 DAC: 7.3
Mass (g)	< 200	52
Volume (mm^3)	$20 \times 100 \times 150$	$12 \times 50 \times 90$

Overall, ADC and DAC modules with optical interconnections can solve easily the transmission and routing of the expected huge amount of data in any type of high throughput telecommunication payload enabling the increase of bandwidth processed and/or the number of beams/channels to be treated, or to support advanced digital processing architectures including beam forming.

ACKNOWLEDGMENTS

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