International Conference on Space Optics—ICSO 2004

Toulouse, France

30 March–2 April 2004

Edited by Josiane Costeraste and Errico Armandillo

Multi-gigabit optical interconnects for next-generation on-board digital equipment

Norbert Venet, Henri Favaro, Michel Sotom,
Michel Maignan, et al.

International Conference on Space Optics — ICSO 2004, edited by Errico Armandillo,
Josiane Costeraste, Proc. of SPIE Vol. 10568, 1056813 · © 2004 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2307960

MULTI-GIGABIT OPTICAL INTERCONNECTS FOR NEXT-GENERATION ON-BOARD DIGITAL EQUIPMENT

Norbert Venet (1), Henri Favaro (1), Michel Sotom (1), Michel Maignan (1), Jacques Berthon (2)

(1) Alcatel Space, 26 avenue J-F. Champollion, BP 1187, 31037 Toulouse Cedex 1, France
(2) CNES, 18 avenue E. Belin, 31401 Toulouse Cedex 4, France

contact : norbert.venet@space.alcatel.fr

ABSTRACT

Parallel optical interconnects are experimentally assessed as a technology that may offer the high-throughput data communication capabilities required to the next-generation on-board digital processing units. An optical backplane interconnect was breadboarded, on the basis of a digital transparent processor that provides flexible connectivity and variable bandwidth in telecom missions with multi-beam antenna coverage. The unit selected for the demonstration required that more than tens of Gbit/s be supported by the backplane. The demonstration made use of commercial parallel optical link modules at 850 nm wavelength, with 12 channels running at up to 2.5 Gbit/s. A flexible optical fibre circuit was developed so as to route board-to-board connections. It was plugged to the optical transmitter and receiver modules through 12-fibre MPO connectors. BER below 10^{-14} and optical link budgets in excess of 12 dB were measured, which would enable to integrate broadcasting. Integration of the optical backplane interconnect was successfully demonstrated by validating the overall digital processor functionality.

1. INTRODUCTION

Many sub-systems of future satellite payloads are expected to incorporate an increasing amount of high-speed digital processing hardware.
In the satellite telecommunications sector, operators are anticipating the emergence of a new market based on broadband communications in the next five to ten years. 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. New satellite payload need to be designed so as to meet such requirements. Only satellites with very large capacity in terms of bandwidth or numbers of circuits would enable to achieve low communication prices. 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. In these conditions, they will likely incorporate large throughput digital processors for filtering, switching and/or regenerating telecom signals.
Digital transparent processors (DTP) are one example of such advanced telecom repeater sub-systems. They have analogue-to-digital (ADC) and digital-to-analogue 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. DTP's are particularly well-suited for routing channels and sub-channels with fine bandwidth granularity in telecom missions with multiple-beam antenna coverage.
Digital beam-forming network (DBFN) refers to other processing architectures that handle digital samples of the electromagnetic waves from many array antenna elements. By achieving the proper combinations of samples and sets of weightings, they enable to form multiple beams and to differently shape them. The accurate control of the beam shape and side-lobe level is one major advantage. Another one is that many contemporaneous and closely spaced beams may be formed, thus making it a very attractive technique for telecom missions where flexible multiple-beam antenna coverage is required.
DBFN also finds application in next generation SAR (synthetic aperture radar) since the antenna pattern can be dynamically and adaptively controlled, and thus implement new tracking or scanning modes, or reduce the effect of directional jammers… Whereas in

conventional architectures, only one high-speed link is required between the instrument output and mass memory input, there would be many links in DBFN-based architectures, namely from the ADC's to the central processor.

In summary, high-speed digital processing is expected to be widely spread in future telecom repeaters and antenna beam-forming networks, in next generation SAR's as well as in data handling units of remote sensors. In this perspective, we have undertaken to assess the benefits and constraints of optical interconnects as a communication technology for supporting the huge amounts of data expected in future digital equipment [2]. In the following, we report on preliminary testing and breadboarding activities.

2. DIGITAL INTERCONNECTS WITH MULTI-GIGABIT THROUGHPUT

The advances of digital circuits over the last few decades have been following what is known as Moore's law. This rule of thumb states that the complexity of integrated circuits (in terms of number of transistors per chip) increases by a factor of two every eighteen months. As digital processing capacities will continue to grow, the pressure will be rapidly shifted to the interconnect function. Future system performance will continue to gain from transistor size reduction, only if interconnect technologies with commensurate data handling capabilities are provided. In many on-board digital processors and equipment, interconnections between printed circuit boards (PCB) are already becoming a bottleneck because of volume, mass, complexity, reliability and electromagnetic compatibility issues. Whereas the operation speed and the number of pins of ASIC's and processors increase, PCB connectors for space applications remain limited in pin number and bandwidth, as a result of physical constraints such as pin spacing, insertion force, alignment …

A technology breakthrough is required to support the expected huge amounts of data. Serial electrical links may temporarily solve some issues, by enabling to increase the bandwidth while reducing the number of connections between PCB's. They will result in higher interconnection densities, provide gigabit-per-second data rates and may relax connector insertion forces. As transmission speeds reach a level where electrical data transmission between racks is then becoming critical, extension technologies recently developed and involving equalizing circuits may be necessary in order to restore degraded signals.

On the other hand, fibre optics holds intrinsic attributes making it the technology of predilection for high-speed communications. Primarily affecting long-distance transmission systems, optical technology has been more recently penetrating in switching, routing and cross-connect systems in the form of short-distance parallel optical interconnects [3].

Fibre optics provides an almost unlimited bandwidth communication medium with extremely low mass and unprecedented connection density. They do allow signals to be transmitted over longer distances than electrical technologies. At the payload scale, this simply means that systems can be designed and tested independently of distance constraints. Other important benefits should result from the suppression of electromagnetic interference and crosstalk issues in backplanes, suppression of impedance mismatches at the connector interfaces, as well as full electrical isolation between transmitter and receiver boards. At the end, this much easier implementation is perceived as a major factor of simplification and thus of shortening of the definition and design, and the assembly, integration and test phases.

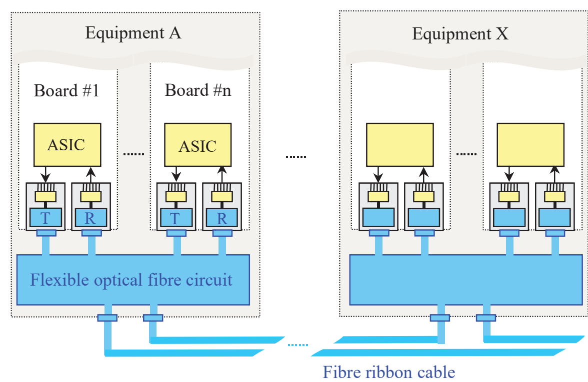


Fig. 1. Optical fibre interconnect for high-speed intra- and inter-equipment communications

Parallel optical interconnect technology has been allocated important R&D efforts for more than ten years. This has included vertical-cavity surface-emitting laser arrays (VCSEL) at 850 nm, laser driver arrays, PIN photodiode arrays, transimpedance amplifier arrays, graded-index multimode optical fibres (GI-MMF), mulitple-fibre ribbon cables, multiple-fibre optical connector, flexible optical fibre circuits… This latter technology allows optical fibres to be routed and

fixed on a flexible substrate in precise, pre-determined paths. Thus, it solves physical fibre management problems and allows accurate and automated manufacturing of custom flexible optical circuits. Fig. 1. shows how all these technologies may be integrated together so as to provide a generic, unique communication means for both intra- and inter equipment high-speed connections.
More advanced interconnects are under study aiming at embedding optical waveguides into conventional PCB's. This includes embedded polymer optical waveguides [4], embedded optical fibre technology, embedded glass optical waveguides… However, no option seems to have emerged yet and there are still many technical issues relating to materials, optical coupling and manufacturing.
Most commercially available high-speed transceiver designs are not designed for space applications, and are generally based on non-hermetic molded-resin packages that are unsuitable for operation in space environment. Whereas the development of such optical devices and technology has been so far, mostly driven by ground telecoms and data-communications, it seems now that there is a variety of other industrial domains (avionics, defence, space, transportation, nuclear industry…) that would take advantage from the availability of optical devices and parts designed or ruggedised for operating in harsh environments [5].

3. ASSESSING PARALLEL OPTICAL INTERCONNECT TECHNOLOGY

We undertook to assess commercial parallel optical interconnect technology, mainly under maturity and performance aspects. From a brief market survey, it comes out that there is a wide offer of commercial products for terrestrial applications [6]. Parallel optical interconnect transmitter and receiver modules providing 12 channels running at up to 2.5 Gbit/s were purchased from a European source. Extensive testing was carried out with a special attention paid to the distribution of the characteristics. As such devices are to implement many links in parallel, it is important that the performance be maintained from one link to the other.
Each transmitter channel was successively fed by a PRBS (pseudo-random binary sequence) generator, with LVDS (low-voltage differential signalling) signals at 2.5 Gbit/s. The average optical power, emitting wavelength, and extinction ratio were measured.
Fig. 2 gives both the average optical power and the extinction ratio for each of the 12 transmitter channels. The output power was found to range from –5 to –3.5 dBm, which is considered as a relatively narrow distribution.

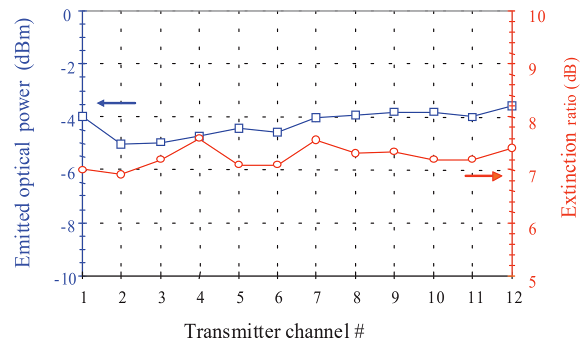


Fig. 2. Optical power and extinction ratio under 2.5 Gbit/s PRBS modulation vs. transmitter channel

The extinction ratio, defined as the ratio of the voltages respectively for logical "1" and "0" levels, is representative of the contrast performed by the transmitter. The larger the extinction ratio is, the better the transmitter performs and the lower is the optical power required to the receiver for discriminating "1" from "0" levels. The distribution of the extinction ratio is also very narrow, each being close to or slightly higher than 7 dB.

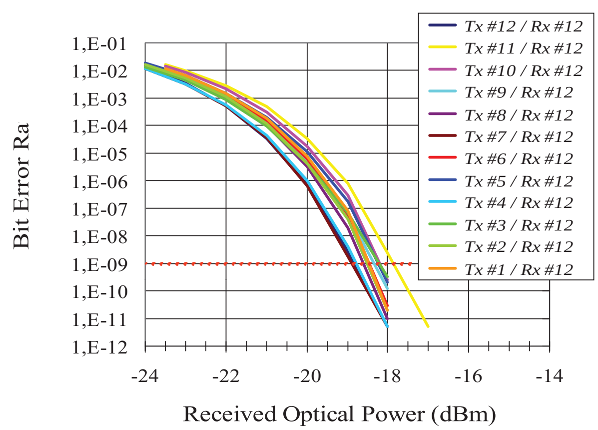


Fig. 3. BER performance under 2.5 Gbit/s, 2^7-1 PRBS modulation vs. transmitter channel

Fig. 3 shows the bit error rate (BER) performance of each transmitter of the multi-channel module. These curves are recorded by measuring the BER variations versus the received optical power on a common reference receiver, namely Rx #12. These curves were measured at 2.5 Gbit/s with 2^7-1 PRBS modulation. These curves are very close to each other, showing that all the transmitters perform very similarly. Detection threshold is commonly defined as the optical power required at the receiver for obtaining a certain BER. The detection thresholds at 10^{-9} range from –18.8 to –17.8 dBm. Extra BER curves were recorded with longer patterns, i.e. 2^{23}-1 PRBS, the electrical spectrum of which features much lower frequency compounds. There was no major patterning effect on the BER performance; the detection threshold degradation, if any, was less than 0.2 dB.

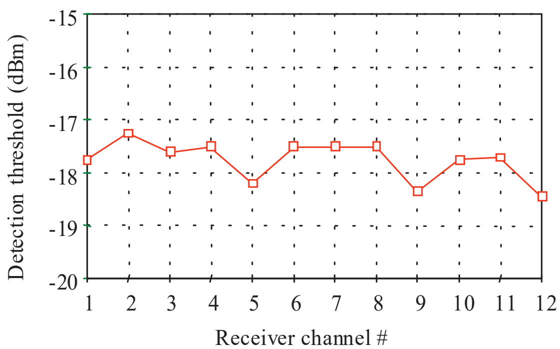
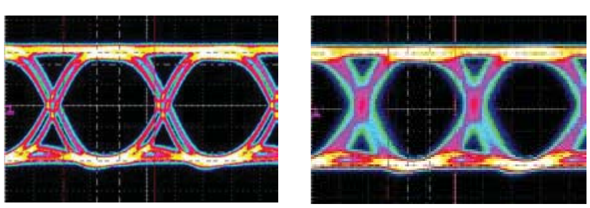


Fig. 4. Detection threshold at 10^{-9} BER under 2.5 Gbit/s, 2^7-1 PRBS modulation vs. receiver channel

Similarly, Fig. 4 shows the detection threshold at 10^{-9} BER for each of the 12 receivers of the same module, with 2.5 Gbit/s, 2^7-1 PRBS modulation. The worst-performing transmitter (i.e. Tx #11) was selected as the reference transmitter to test each of the receivers. Again the receiver performance distribution is low as detection thresholds range from –17.3 à –18.3 dBm.



(a) with more than -10 dBm optical power at the receiver: BER < 10^{-14}

(b) with about -17 dBm optical power at the receiver: BER ~ 10^{-11}

Fig. 5. Eye-diagrams at 2.5 Gbit/s for 2 different levels of optical power falling on the receiver

Fig. 5. shows the eye-diagrams as observed at the receiver output for various optical power levels. Note that Fig. 5 (b) corresponds to a link with more than 12 dB optical loss. In both cases, the eye-diagrams are well-shaped and perfectly open.

An optical link budget figure may be derived from these preliminary tests. The worst-case power available at the transmitter output being –5 dBm, the worst-case detection threshold being of –17.3 dBm, the optical link loss budget is about 12.3 dB. This optical link budget figure is a first estimate as it does not take into account all possible transmitter-to-receiver connections. However, it is clear that such an optical link budget is well beyond what is strictly needed for straight point-to-point connections, and that this might be used to include other functionality such as passive broadcasting or redundancy switching as well.

4. MULTIGIGABIT OPTICAL BACKPLANE BREADBOARD DEMONSTRATOR

A backplane interconnect demonstrator was breadboarded in order to assess parallel optical link technology under the system environment and practical constraints of a space digital processor application. The equipment selected as study case was a digital transparent processor. Fig. 6. shows one possible digital transparent processor architecture, modified so as to include an optical backplane interconnect.

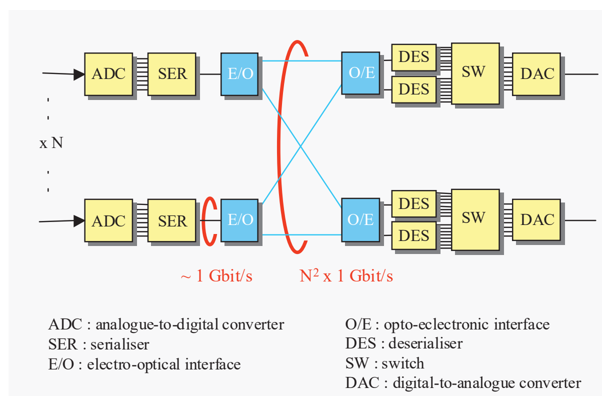


Fig. 7. An example of digital transparent processor architecture with optical interconnect (in blue)

As a matter of example, each access with tens of MHz bandwidth processing capability would generate after sampling a data flow of 1 Gbit/s. As these data need to be broadcast from any input to all output accesses, more than tens of Gbit/s have typically to be supported by the core interconnection network.

In order to minimise the development efforts, existing prototype rack and boards were re-used instead of developing entirely a new architecture with an optical interconnect. The unit selected for the demonstration featured 8 input and 8 output ports, and provided channel routing. Thus, the optical transmitter and receiver modules were inserted in the unit by using additional mezzanine boards as shown in Fig. 6. Seralisers at 1 Gbit/s were used to feed the transmitter modules. Deserialisers were also implemented at the output of the receiver modules.

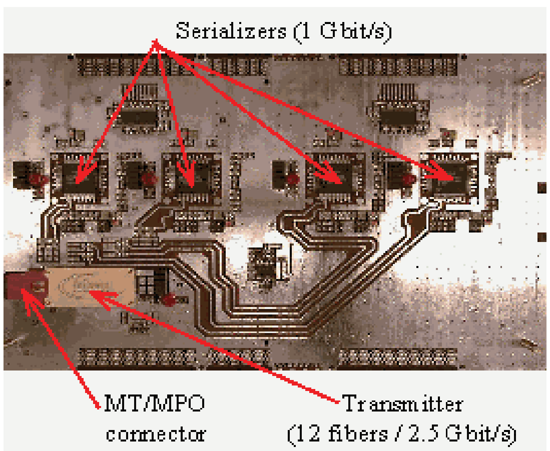


Fig. 6. O/E transmitter mezzanine board

A flexible optical fibre circuit was designed and developed so as to route the optical signals from board to board. It was connected to the multi-channel optical transmitter and receiver modules through MPO connectors based on industry-standard 250-micron pitch MT ferrule, and achieving reliable low-loss connections. Average optical connector loss was found to be equal to 0.23 dB with a maximum figure of 0.7 dB.

Next tests consisted in checking that the insertion of the flexible optical circuit was not introducing any performance degradation. Fig. 7 is a view of the experimental set-up. BER curves were recorded for a number of links going through the flexible optical circuit. They were compared to those obtained by directly connecting the same transmitter and receiver, i.e. without going through the optical circuit. There was no change of the overall shape of BER curves, no indication of any BER floor, no drastic penalty due the insertion of the optical fibre circuit. At most, there was an average 0.25 dB detection threshold degradation.

In addition, for each of the 19 optical fibre routes through the flexible circuit, the BER was measured to be less than 10^{-11}. One of these links was continuously tested, and ran error-free over a 2-day period, thus demonstrating a cumulated BER figure at least better than 10^{-14}.

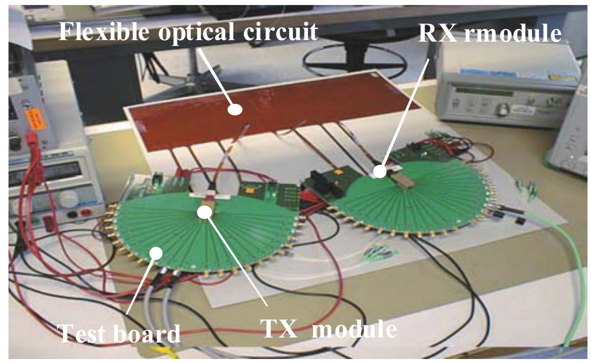


Fig. 7. Experimental set-up for testing the flexible optical fibre circuit

Lastly, it was investigated to which extend it was possible to maintain some synchronism between data channels going through the optical circuit in parallel.

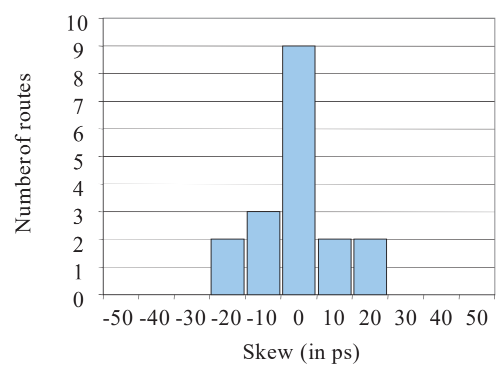


Fig. 8. Distribution of differential delays through the optical fibre routes

The differential delay, also referred to as skew, experienced by separate optical routes was measured. Fig. 8. shows the distribution of these delays with respect to an average trip time over the 19 optical fibre routes. The skew was found to be within $\pm$ 25 ps, i.e. less than 12.5% of the bit time at 2.5 Gbit/s. Attributing this skew to differential optical path lengths, means that the 19 optical fibre routes were equalised within ± 5 mm. This shows how the implementation of flexible optical fibre circuits is well-mastered, and that synchronism of channels travelling in parallel through such an optical circuit, could be maintained if required.

Once tested separately, all the building blocks were assembled and integrated in the breadboard demonstrator composed of the processor prototype unit and of the optical fibre interconnect. Fig. 9 is an overview of the integrated breadboard demonstrator.

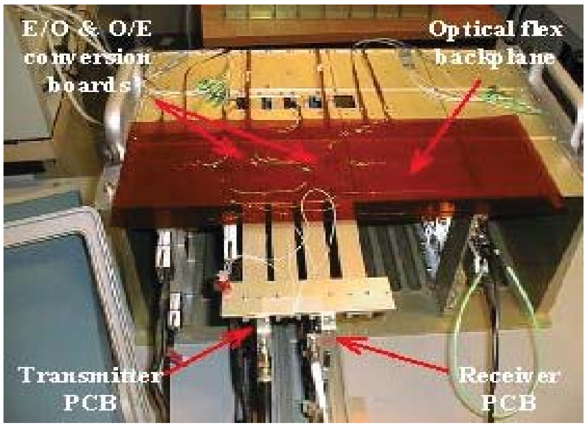


Fig. 9. Integrated optical backplane interconnect breadboard

The integration of the optical backplane interconnect was validated by successfully demonstrating the overall digital processor functionality. It was checked that an analogue signal could be properly routed from an input access board with a transmitter PCB, through the optical interconnect to an output access board with a receiver PCB.
One of the most striking facts during the integration phase was that very few difficulties were encountered. This reinforced our perception that optical interconnect technology, operating with large system margins, may bring error-free operation without any tuning. In practice, this will have impact in shortening the industrial development cycle.

4. CONCLUSION

The introduction of digital processing in many future satellite payload sub-systems calls for efficient interconnect technology. Parallel optical fibre links hold the potentials to meet these requirements. They may provide a generic medium supporting both intra- and inter-equipment communications, with almost un-limited bandwidth, distance-independent performance, unprecedented connector density and low mass cabling. Other major advantages for intra-satellite system applications stem from the suppression of EM crosstalk issues, suppression of impedance mismatches, full isolation between transmitting and receiver ends, simplification of routing… All together these things are expected to substantially simplify and shorten both the design and integration phases.

Extensive testing on commercial-grade multi-channel transmitter and receiver modules revealed low channel-to-channel performance distributions, as an indication of a certain technological maturity. An optical link loss budget of about 12 dB was found to be available. In addition to provide some safe system margins, this may allow for the implementation of extra functions such as broadcasting or redundancy switching.
A breadboard demonstration based on a digital transparent processor prototype enabled to assess the potentials of these technologies from a very practical point of view. Designing this particular equipment from the start with optical interconnect technology would have enabled the designer to:
- reduce the connector size and arrange more efficiently several functions on the same board,
- extend the connectivity (number of input/output ports) of this equipment.
Equally important is that almost no difficulty was encountered during the integration phase, thereby confirming that such a technology may contribute to simplify and shorten the development cycle.

However, the adoption of parallel optical interconnect technologies in digital processing units for space applications will not be straightforward. In particular, this will require new designs and further developments in the packaging aspects [7] before qualification and deployment in space systems. On the other hand, synergies may exit with other highly-demanding industrial domains that would also benefit from the availability of such optical modules designed from the start for harsh environments.

6. ACKNOWLEDGMENT

This work has been partly supported by the French National Space Agency (CNES).

7. REFERENCES

[1] J-D. Gayrard, M. Maignan, M. Sotom, B. Benazet, N. Venet, Evolution of telecommunication payloads: the necessity of new technologies, *20th AIAA ICSSC*, Montreal, Canada, 13-15 May, 2001.

[2] J. Loesel, J. Berthon, M. Maignan, M. Sotom, B. Benazet, A. Barthere, N. Venet, T. Clarenson, Les techniques optiques dans les charges utiles de télécommunications spatiales, *OPTRO-2002*, Paris, France, 14-16 January, 2002.

[3] A. F. J. Levi, Optical Interconnects in Systems, *Proceedings of the IEEE*, vol. 88, 750-747, June 2000.

[4] J. Moisel, J. Guttmann, H.-P. Huber, O. Krumpholz, M. Rode, Optical Backplanes utilizing Multimode Polymer Waveguides, *Optics in Computing 2000*, SPIE proceedings vol. 4089, Quebec City, Canada, 18-23 June, 2000.

[5] C. H. Chalfant, F. J. Orlando, P. J. Parkerson, Parallel spaceborne fibre optic data bus physical layer, *SPIE Conference on Photonic Processing Technology and Applications*, Orlando, Florida, April 1998.

[6] http://www.paralleloptics.org/

[7] C. Chalfant, F. Orlando, P. Parkerson, Photonic Packaging for Space Applications, *IMAPS Advanced Technology Workshop on Optoelectronics*, Bethlehem, Pennsylvania, 11-14 October, 2001.