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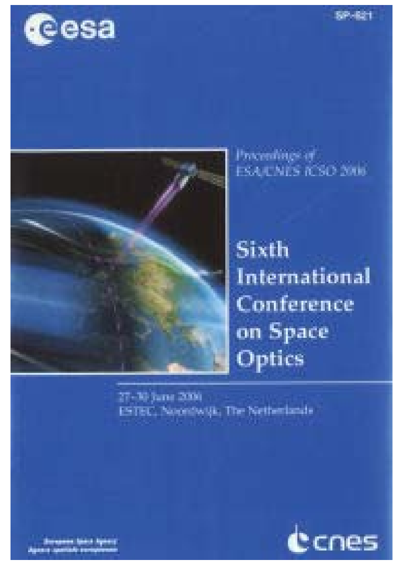

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WDM BASED MULTIGIGABIT OPTICAL BACKPLANE FOR ON-BOARD APPLICATIONS

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ABSTRACT

An optical backplane based on Wavelength Division Multiplexing (WDM) for onboard data and signal handling is introduced. It is a tunable transmitter fixed receiver architecture incorporating an NxN Arrayed Waveguide Grating (AWG) element for passive data routing between the nodes. In conjunction with star couplers both unicast and multicast capabilities are offered. The control plane has been implemented on a high-speed FPGA and a four-node demonstrator has been built. Bit-Error-Rate (BER) versus power incident on the receiver, employing three different AWGs, has been measured at a data rate of 10Gbps per link. A total switching time of 500ns has been achieved, leading to more than 95% efficiency with packet lengths greater than 10KBytes.

1. INTRODUCTION

The need for high bandwidth in interconnection networks due to the increased processing power and latency requirements has led to the investigation of the potential of optical interconnects at the backplane level of high-end computing systems [1,2]. Since the requirement for on-board data and signal handling is expected to increase dramatically in the near future, for example, the introduction of high data rate sensors such as the Synthetic Aperture Radars (SARs) and high-resolution cameras involves vast amounts of memory and on-board signal processing before down linking in order to reduce link capacity requirements, the potential use of such systems in space applications should be investigated.

Wavelength Division Multiplexing (WDM) is a widely applied technique in long haul telecommunications and Metropolitan Area Networks (MANs) [3], which offers increased bandwidth through a single optical fiber. However, the advantages of WDM are not extensively investigated for chip-to-chip and board-to-board interconnects. In [4] a WDM based optical backplane for high-speed IP routers is proposed using passive routing of data packets through the network. A prototype system working at a data-rate of 40Gbps is presented using a PC-based controller to guarantee collision free operation.

The goal of our work is to assess how current developments in optical backplane interconnections can be applied to the next generation of spacecraft data handling and communication systems and to design and built-up a prototype demonstrator. In this paper we present a WDM optical backplane using three different Arrayed Waveguide Gratings (AWGs) [5], which exhibit different characteristics in terms of size, sensitivity to temperature and polarization and performance. A four-node demonstrator has been set-up using tunable transmitters and fixed receivers and high-speed FPGAs implementing a hybrid centralized-distributed control mechanism. Bit-Error-Rate (BER) measurements versus power for static backplane operation and under dynamic reconfiguration are reported for the three AWGs used.

2. BACKPLANE ARCHITECTURE and IMPLEMENTATION

2.1 Architecture

The backplane architecture is shown in figure 1. In general, N nodes are connected to an NxN AWG routing element [5] and by using different wavelengths they can exchange data with any other node. This architecture is a Tunable Transmitter Fixed Receiver (TTFR) configuration meaning that every node can be tuned to send data to any of the permissible wavelengths, while the receiver accepts incoming data in all wavelengths. By using a NxM AWG with M>N and adding extra star couplers, multicast features can also be implemented.

The passive wavelength router transparently implements the network connectivity on the physical level together with the laser circuitry. By using this combination of tunable transmitters, fixed receivers and fixed communication paths in the router, responsibility for adding more flexibility in the network is put on higher network levels. Although the AWG by itself is a non-blocking routing element, collisions may arise on the overall backplane when two or more nodes are

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transmitting simultaneously to a single node. Thus, an arbitration mechanism should be used for the collision free operation of the backplane.

2.2 Implementation

A four-node prototype system has been built based on this architecture. In order to reduce implementation cost and enable fast switching experiments, two of the nodes have sending and receiving capability, while the other two nodes possess burst-mode receivers only.

1) Wavelength router

Three different AWGs have been used and tested, namely a commercially available 4x4 AWG in silica-on-silicon (SoS), a research prototype 4x4 AWG in silicon-on-insulator (SOI) [6], and a prototype 8x8 AWG in polymer technology. The later has been combined with three star couplers in order to demonstrate multicasting capabilities of the system. The characteristics of the three AWGs used are summarized in Table I.

2) Transponders

The transponder modules used employ a common of the shelf laser-less transponder driven by an external fast wavelength switchable laser source. The transponders are capable of sending and receiving 10Gbps data streams and communicate electrically with the data and control module described in sub-section B.3. The tuneable lasers have 80 50GHz-spaced channels from 1528nm to 1563 nm (C band). During switching, the output of the laser is blanked to avoid disruption of other communication channels, and when blanking is removed the laser is actively locked to the correct wavelength. For all possible wavelength transitions the maximum switching time is <200ns and the wavelength is specified to be within ±2.5GHz of the expected value. As the demonstrator uses a small subset of the wavelengths the typical switching time is <100ns.

The receivers are based on PIN photodiodes. Two of them are part of the transponders and incorporate an optical amplifier for dynamic range extension, while the other two are burst-mode receivers (in-house developed by Intune Technologies).

3) Control units

The data and control plane of the backplane has been implemented using the Stratix-II® high speed FPGAs of Altera. Concerning the data plane every node generates outgoing data packets (comprising of a variable length receiver lock-up pattern, a fixed start-of-data pattern and a 2^{23}-1 pseudorandom bit sequence), processes incoming data, sets up communication links and performs Bit Error Rate (BER) measurements. The internal data-path is implemented using a 64-bit architecture operating at a core frequency of 155.52 MHz in order to produce the required serial data rate of 9.953 Gbps. A 300-pin MSA compatible connector is used to interface the FPGA with the optical transponders. The control of data flow within the backplane is implemented as a hybrid form of centralized/distributed control, where all nodes contain predefined routing tables and communication schemes and a master node is responsible for controlling synchronization between the nodes. The wavelength address on the tunable laser module is selected through a proprietary Fast Wavelength Assignment Interface. The control boards are connected through a JTAG interface to a PC for programming the FPGAs and for data retrieval.

A four-node system, with two full duplex nodes and two receive only nodes, is implemented as shown in Figure 2. All nodes operate at a full data rate of 10Gb/s, therefore this network has a two way capacity of 20Gb/s or an aggregate routing capacity of 60Gb/s.

3. TEST RESULTS

Initially, the error free operation of every node has been verified using electrical and optical loopback connections. No errors have been recorded for more than 10 hours of continuous operation leading to a BER $<10^{-15}$.

Subsequently, evaluation of the overall system performance and comparison of the three routing elements was performed. External attenuation of the optical signal was used in order to obtain BER vs received power curves. The first set of measurements aimed to get the single channel BER figure by setting-up a single point-to-point connection through the routing element. The results are summarized in Figure 3. The SOS component presents the smaller variation between different channels (<0.2 dB), while the polymer and the SOI AWGs are more sensitive to wavelength change. The variation observed in the SOI AWG is partially due to the fact that the tunable laser output and the AWG input wavelength are not exactly matched in all cases. Unicast and broadcast BER measurements performed using the polymer AWG showed a 0.5 dB power variation between all four channels for broadcast operation, which is mainly due to insertion loss variations of the external couplers used to implement the broadcasting scheme.

The next set of experiments intended to determine the influence of incoherent and coherent cross-talk and the power penalty introduced by single and multiple channel cross-talk. Initially, power penalty due to single source cross-talk was measured. The cross-talk level (CL) was being adjusted, when necessary, by attenuating the optical power of the appropriate transmitter. The power penalty for incoherent cross-talk was found to be 0.05 dB for the SoS AWG at a CL of 25 dB and 0.2 dB for the Polymer device at a CL of 22.5 dB. For the SOI AWG, the power penalty varied from 0.1 dB at a CL of 19 dB to 1dB at a CL of 11.1 dB. The power penalty due to coherent cross-talk presented greater variations, as expected. For the SoS device, it was in the range of 0.05 – 0.075 dB (for different optical paths) at a CL of 25 dB and increased to 0.2 – 0.3 dB as the CL decreased to 13.4 dB with attenuation of the optical signal. The SOI AWG gave a 2dB power penalty at a CL of 14.1 dB that reduced to 0.2 dB as the CL increased to 20.1 dB by attenuating the signal causing the cross-talk. The polymer device experienced the greater sensitivity to coherent cross-talk as the power penalty was 1.25 dB at a CL of 22.5 dB and further increased to 3 dB at a CL of 20 dB. All power penalties were measured at a BER of 10^{-10}. Finally, an external modulated tunable source was used with the SoS AWG as a third transmitting node, since as mentioned earlier only two transponders were available. The cumulative power penalty due to the two cross-talk sources increased to 0.45 dB at a CL of 13.4 dB (Figure 4) which implies the effect is additive.

The tests reported up to now are static since the backplane configuration does not change during the test. A set of dynamic tests has been also performed using the burst-mode receivers of nodes 2 and 3. Two scenarios have been examined: always on and off-to-on switching. In the always-on case nodes 0 and 1 send data to nodes 2 and 3, respectively, for a specific time interval and after that a switching occurs, so that node 0 sends to 3 and 1 to 2. In the on-to-off case the receiver under test gets data from a transmitting node (i.e. node 0), thereupon gets no data for some time and finally receives data from another node (i.e. node 1). This represents the worst case, since the receiver locks on the incoming data after a period of darkness. In both cases, constant crosstalk is always present as both transmitters are always on. BER measurements for a fast off-to-on switching have shown no degradation at backplane operation using a preamble length of 500 ns and a packet length of 4 sec. Thus, fast switching in the range of 600 ns (laser switching time <100 ns) can be achieved.

4. CONCLUSIONS

A four-node wavelength routed multigigabit optical backplane, based on a passive AWG router and tunable transponders, has been demonstrated. Three types of routers have been successfully tested: in silica-on-silicon (SoS), in silicon-on-insulator (SOI) and in polymer. The control plane of the backplane is implemented as a hybrid form of centralised/distributed control with a master node responsible for triggering events and controlling synchronisation and it has been realized using high-speed FPGAs. BER measurements vs optical power, for static and dynamic backplane configuration using 10Gpbs data streams, reveal the scalability of the architecture to large number of ports with switching times less than 500 ns.

5. ACKNOWLEDGEMENT

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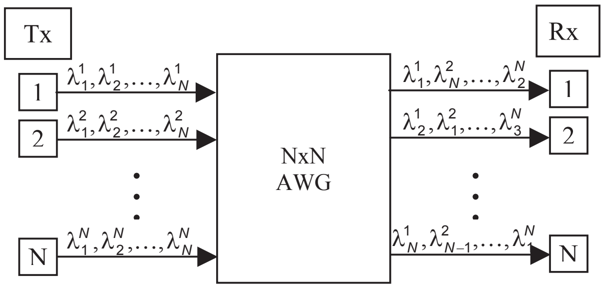

Fig. 1. Basic backplane architecture with NxN AWG.

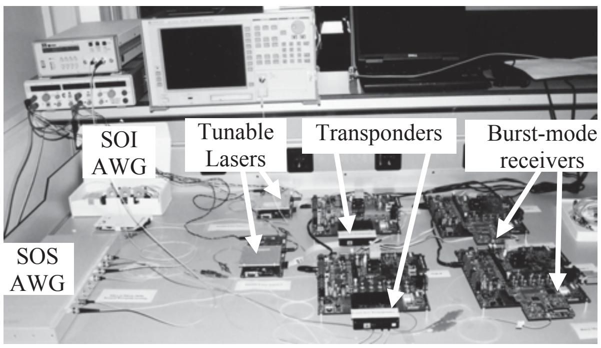

Fig. 2. Photograph of the 4-node demonstrator set-up.

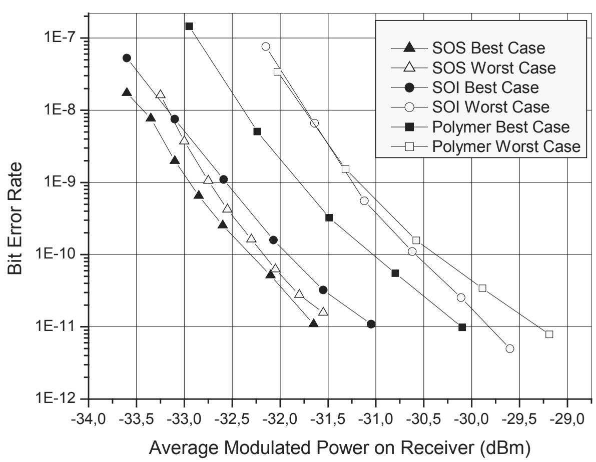

Fig. 3. Back-to-back BER measurements for the SOS, SOI and Polymer AWGs.

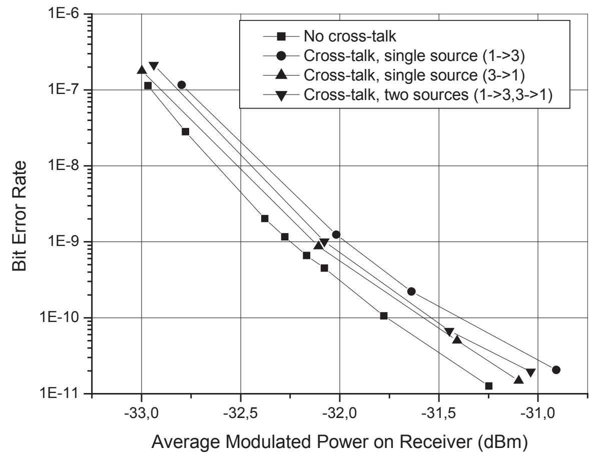

Fig. 4. BER measurements under the presence of coherent cross-talk (CL=13.4db, AWG: SOS)

AWG type	No. of I/Os	Size (mm^2)	Insertion Loss (dB)	Cross-talk (dB)	Temp. depend.	Polar. depend.
SOS	4x4	3000	7-9	-25 dB	Low	Low
SOI	4x4	2	12-14	-12 dB	High	High
Polymer	8x8	1000	< 12	< -20	Low	High

Table I. Basic characteristics of the AWGs.