

Packet-by-packet wavelength-routing interconnect technique for 5 Tbit/s switching system

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A packet-by-packet wavelength-routing interconnect technique for a 5 Tbit/s switching system with a three-stage architecture has been demonstrated. The technique uses an optical wavelength division multiplexing (WDM) link and dynamic bandwidth-sharing among wavelengths. The inter-stage, electro-optical interconnection subsystem was fabricated using very compact 2.5 Gbit/s, eight-wavelength WDM transmitters/receivers and an arrayed-waveguide grating router.

Introduction: To enable the continuous growth of data communication traffic, a Tbit/s-class node system for the backbone network will need to be developed in the near future. We have already developed a 640 Gbit/s asynchronous transfer mode (ATM) switching system, OPTIMA-1 (optically interconnected distributed multi-stage Tbit/s-ATM switching network architecture), that has a non-blocking, three-stage switch architecture with eight 80 Gbit/s basic switch-elements at each stage [1, 2]. This architecture has the advantage of enabling the construction of a large switch by simply adding identical unit switches. Extending the scale of OPTIMA-1 by eight times, we have proposed the OPTIMA-2 architecture, using packet-by-packet wavelength-routing based on 2.5 Gbit/s eight-wavelength WDM links and dynamic bandwidth-sharing [3]. Based on that proposed architecture, this Letter reports the implementation of the very high-speed intra-switch WDM packet-by-packet switching interconnection subsystem and a demonstration of its switching operation.

System architecture: The OPTIMA-2 switching system architecture is shown in Fig. 1. Each stage consists of 64 basic switch-elements. A basic switch-element has eight 10 Gbit/s input and output ports, providing a total switching throughput of 80 Gbit/s. The output ports of all the basic switch-elements at one stage are connected to the input ports of those at the next stage by an optical wavelength division multiplexing (WDM) link. Incoming packets are segmented into sequential cells, then switched electrically in the basic switch-element and routed optically between the output port and the input port by the arrayed-waveguide grating (AWG) wavelength router.

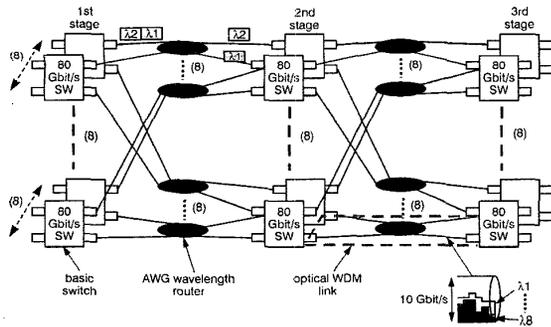


Fig. 1 Architecture of OPTIMA-2 switching system

The eight-wavelength WDM link has a maximum bandwidth of 2.5 Gbit/s per wavelength, enabling dynamic bandwidth sharing within the total bandwidth of 10 Gbit/s for each switch-element port. The effective link bandwidth of each wavelength can be dynamically adapted from 0 to 2.5 Gbit/s (i.e. more than 1/8th of 10 Gbit/s). This makes it possible to expand the scale of the system without decreasing the statistical multiplexing gain [3]. It also provides robustness against traffic imbalance.

The optical routing between stages is controlled electrically. The system autonomously monitors the traffic in each wavelength and controls the flows of cells among wavelengths by using an internal header appended by the line interface unit of the system. Each cell derived from a particular packet is assigned to an appropriate wavelength selected by the system. Thus the total switching throughput of the entire system is improved to 5 Tbit/s.

Inter-stage interconnection: The inter-stage, electro-optical interconnection subsystem consists of sender ports, receiver ports, WDM transmitters/receivers, and an AWG wavelength router, as shown in Fig. 2. The sender and receiver ports perform electrical processing, and the WDM transmitter and WDM receiver provide optical interfaces (i.e. EO/OE conversion). At the sender port, the 10 Gbit/s electrical signal from the output port of a switch-element is received as a cell flow and distributed to eight channels using address filters referring to the routing bits in the internal header. The cells are then accumulated in buffers for speed conversion to 2.5 Gbit/s. The destination of each buffer is equal to the next stage switch member. This means that these buffers act as virtual output queues. The 2.5 Gbit/s electrical signals are then converted to optical signals of the corresponding wavelength and optically coupled onto a single optical fibre by the WDM transmitter. The multiplexed optical signals are directed to different optical fibres wavelength-by-wavelength and multiplexed again into each fibre by the AWG wavelength router; i.e. optical packet-by-packet wavelength-routing is performed. These optical signals are decoupled into individual wavelengths and converted to electrical signals by the WDM receiver. At the receiver port, the cells extracted from each wavelength are buffered, scheduled, and fed as a 10 Gbit/s bandwidth signal to the input port of the next-stage switch-element.

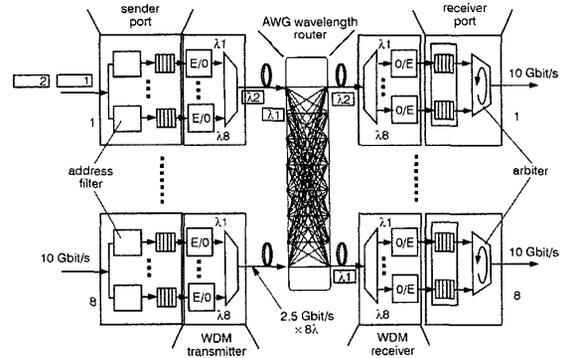


Fig. 2 Inter-stage electro-optical interconnection subsystem

The electrical processing functions, such as address filtering in the sender port or arbitration in the receiver port, were implemented using field programmable gate array (FPGA) devices manufactured with 0.18 μm CMOS technology. Figs. 3a and b show views of these implementations on printed circuit boards (PCBs) for a sender port and receiver port, respectively. The input and output signals are demultiplexed and multiplexed, respectively, to operate the FPGAs at the wire speed.

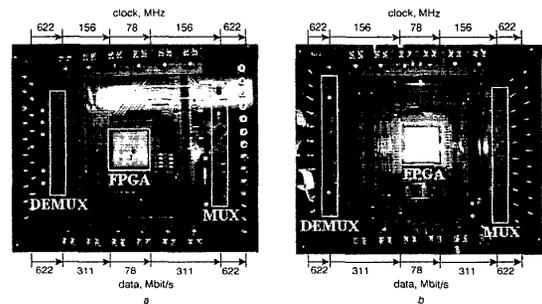


Fig. 3 FPGA board implementations of sender port and receiver port

a Sender port
b Receiver port

Figs. 4a and b show the WDM transmitter and the WDM receiver, respectively. The optical interface modules were fabricated compactly using a planar lightwave circuit (PLC) platform, on which the AWG coupler/decoupler was formed. We also used PLC hybrid integration to directly mount optical devices such as laser diodes (LDs) and photo-detectors (PDs) onto PLCs. The electrical interface of each 2.5 Gbit/s channel is demultiplexed to four 622 Mbit/s signals to ease the PCB patterning restriction. The WDM transmitter/receiver and the AWG

wavelength router have been confirmed to work with a bit-error-free operation consistent with the optical power budget design of the link [4]. Fig. 5a shows its eye-diagrams corresponding to λ .

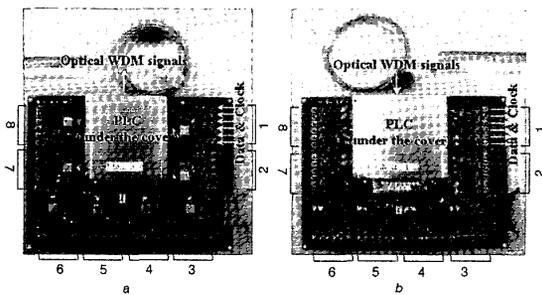


Fig. 4 WDM transmitter and WDM receiver

a Transmitter
b Receiver

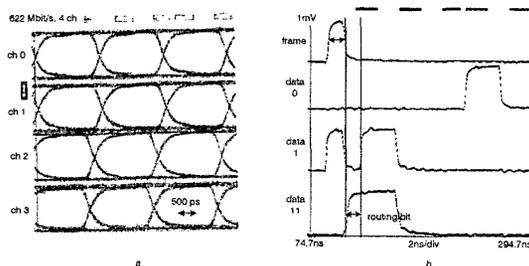


Fig. 5 Eye-diagrams of WDM optical link and bit-sequences of inter-stage, electro-optical interconnection subsystem

a Eye-diagrams
b Bit-sequences

Operational results: We experimentally examined the operation of the inter-stage, electro-optical interconnection subsystem. Test cells generated by a pulse pattern generator were transmitted through the sender port, receiver port, and WDM transmitter/receiver. Fig. 5b shows an example of the bit-sequences obtained as output from the receiver port. The Figure shows the framing signal at the top, while the others are 1:16 demultiplexed data signals with a bit rate of 622 Mbit/s. The framing signal is regenerated from the bit stream by using the frame synchronisation pattern in the cell header, and it corresponds to the head of the cell. The bottom row is the eleventh bit of the 16 data bits, and the time region between the two vertical lines corresponds to the routing-bit field in the cell header. The results show that cells were properly converted to their assigned wavelengths according to their routing bits. The basic operation of the inter-stage, electro-optical interconnection subsystem was thus successfully confirmed by this experiment.

Conclusion: We have fabricated an intra-switch, electro-optical interconnection subsystem for a Tbit/s-class switching system using dynamic bandwidth sharing of the 2.5 Gbit/s bandwidth on an eight-wavelength WDM link. We confirmed the subsystem's operation experimentally. Thus, a packet-by-packet wavelength-routing interconnect technique to achieve a 5 Tbit/s total-throughput switching system has been established.

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25 October 2001

Electronics Letters Online No: 20020082

DOI: 10.1049/el:20020082

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Polarisation-mode dispersion monitoring technique based on polarisation scrambling

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A simple technique that could be used to monitor the first-order polarisation-mode dispersion in wavelength-division multiplexed networks is proposed. This technique, based on the polarisation scrambling, could measure the polarisation-mode dispersion with accuracy of ± 2 picoseconds even with the existence of large chromatic dispersion.

Introduction: The capacity of lightwave networks has been increased significantly recently by using a large number of high-speed (> 10 Gbit/s) wavelength-division multiplexed (WDM) channels. In these networks, one of the most important limiting factors would be the polarisation-mode dispersion (PMD) [1]. To overcome this limitation, there have been substantial efforts to develop the technologies for PMD compensation. However, in dynamically reconfigurable WDM networks, PMD of each channel could be changed frequently. In addition, PMD is sensitive to ambient temperature [2]. Thus, for efficient PMD compensation it is essential to monitor the PMD accurately. Previously, it has been reported that the signal distortion caused by PMD could be estimated by measuring the half-frequency component of the baseband signal in non-return-to-zero (NRZ) format [3-5]. However, the accuracy of these techniques could be affected significantly by chromatic dispersion. In this Letter, for the first time to our knowledge, we propose and demonstrate a simple technique that can monitor the first-order PMD even with the existence of large chromatic dispersion.

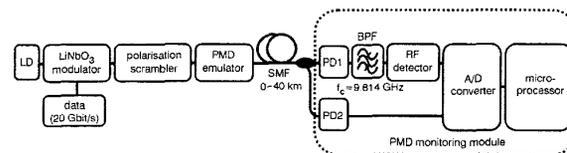


Fig. 1 Experimental setup

PD: photodetector; BPF: bandpass filter

Theory and experiment: Fig. 1 shows the experimental setup used to demonstrate the principle of the proposed technique. The output power and operating wavelength of the distributed feedback (DFB) laser were 3 dBm and 1550 nm, respectively. We modulated the DFB laser at 20 Gbit/s (pattern length $2^{31} - 1$) using a LiNbO₃ modulator. The modulated signal was polarisation-scrambled by rotating wave plates [6]. The scrambled signal was first sent to the PMD emulator to simulate the first-order PMD. The output of the PMD emulator traversed through the singlemode fibre (0-40 km) and split into two input ports of the PMD monitoring module. The high-speed photodetector (PD1) was used to detect the 20 Gbit/s NRZ signal. The low-speed photodetector (PD2) was used to measure the optical power. The output of PD1 was filtered using a bandpass filter (centre