Optical WDM Packet-by-packet Interconnection Modules for 5-Tb/s Electro-optical Switching System

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Abstract

We have demonstrated optical WDM (wavelength division multiplexing) packet-by-packet interconnection modules for a 5-Tb/s electro-optical switching system. Interconnection is performed by electrical control of the data flow and optical wavelength-routed switching, for which we fabricated WDM transmitter and receiver modules that have 2.5-Gb/s, 8-wavelength optical channels. A channel spacing of 500GHz provides the wavelength precision needed to meet the optical power budget design. Optical WDM interfaces are assembled very compactly using planar lightwave circuit hybrid integration technology. The basic operation of the modules was successfully confirmed.

Introduction

In next-generation networks, backbone systems will need to be high-speed and high-capacity to deal with the rapid and continuous growth of data traffic loads. We have been developing an electro-optical switching architecture called OPTIMA (Optically interconnected multi-stage ATM switch architecture) which has the potential to provide multi-Tb/s throughput using optical WDM (wavelength division multiplexing) intra-switch interconnection [1]. The previously developed OPTIMA-1 has a switching capacity of 640-Gb/s. To improve it, we have proposed an extended switch architecture, OPTIMA-2 [2]. In this paper, we describe the optical WDM packet-by-packet routed interconnection modules for OPTIMA-2.

Overview of Switch Architecture

OPTIMA has a nearly non-blocking 3-stage switch architecture. Each stage consists of 80-Gb/s basic switch-elements, each the size of a postcard as a result of using ceramic multi-layer MCMs (multi-chip modules) [3]. This architecture is highly scalable and can be extended simply by adding identical switch-elements. In addition, OPTIMA enables significant enhancement of the switch capacity by applying optical WDM technology to the inter-stage interconnection. Optical interconnection overcomes the bottleneck of electrical interconnection and reduces the number of cables.

OPTIMA-1 has eight switch-elements in each stage, and their eight 10-Gb/s inputs and outputs are applied to 8-wavelength inter-stage WDM interconnection. Thus, the switching capacity is 640 Gb/s. Extending the scale of OPTIMA-1 by m times, where m is the number of wavelength of WDM interconnection, OPTIMA-2 has total switch throughput of (80*8*m) Gb/s. Figure 1 shows the architecture of OPTIMA-2. Each stage has (8*m) switch-elements, extended m times in the orthogonal direction with respect to the structure of OPTIMA-1. Each 10-Gb/s interface is divided among the m-wavelength WDM interconnection in OPTIMA-2.

Packets are sent as data units from one output interface and distributed into wavelength-channels and routed to the next stage according to their wavelengths. Data units are assigned an appropriate wavelength in order to optimize the bandwidth utilization, according to the information carried in their headers and traffic circumstances obtained from the system monitoring signals. The optical routing between stages is controlled electrically, i.e., electro-optical packet-by-packet switching is performed.

The physical bandwidth in each wavelength channel is set to more than (10/m)-Gb/s in order to efficiently use the total bandwidth of 10 Gb/s for each switch-element port when traffic is non-uniform [4]. The effective bandwidth of each wavelength can be dynamically adapted from 0 to
The following section describes the design and fabrication of WDM transmitter module and receiver module.

**Optical WDM Link**

For optical WDM interconnection systems, precise control of wavelength is required. An offset of central frequencies between the light source and the filters (AWGs) in each wavelength channel results in excess optical losses. The number of wavelengths is determined according to the required wavelength accuracy. First, we considered the power budget without wavelength deviation of the laser diode (LD) and AWG, then we allotted its margin of optical loss to absorb the excess loss coming from the frequency offset between LD and AWG. Figure 2 shows the level diagram of our optical link. We use a distributed feedback laser diode (DFB-LD) with output power of 9.5 dBm. The insertion loss of the AWG wavelength coupler (the wavelength multiplexer of the WDM transmitter module) was estimated to the 10 dB including coupling loss with the LD. Also, insertion losses of the AWG wavelength router and AWG decoupler (wavelength demultiplexer of WDM receiver module) are approximated 10 and 5 dB respectively. These losses are considered to

![Figure 1 Architecture of OPTIMA-2.](image)

![Figure 2 Optical power budget.](image)
include the wavelength deviations of the LD and AWG themselves. Thus, the peak optical input power is -15.5 dBm. The output voltage was calculated to be 585 mV using conversion efficiency of 0.8 A/W for the photo detector (PD) and transimpedance of 26 kΩ for the pre-amplifier. Therefore, the margin of optical loss is 7.7 dB when the necessary input voltage of the receiver IC is 100 mV. Through the link, the optical signals traverse three AWGs: coupler, decoupler, and wavelength router. Considering the worst case in which the wavelength deviations there are all in the same direction, the acceptable excess loss at an AWG is limited to one third of the total margin i.e., 2.5 dB.

For the 1550-nm band (C band), the frequency spacing is approximately \((4000/m)\) GHz, where \(m\) is the number of wavelengths. As the AWG transmission bandwidth for each wavelength is wide, the requirement for wavelength precision is mitigated. On the other hand, the crosstalk between wavelengths increases. The AWG's transmission profile can be approximated by the Gaussian form. Thus, the relationship between the crosstalk with the next wavelength channel and the excess loss at the AWG is calculated for the ratio of bandwidth (3 dB full width) to frequency spacing. Figure 3 shows plots of this calculation. We chose the (bandwidth/spacing) to be 0.6 in order to suppress the crosstalk to -20 dB when the excess loss is around 2.0 dB.

Now, based on the Gaussian approximation again, the acceptable frequency offset between the LD and AWG is determined for the AWG excess loss at the fixed (bandwidth/spacing) ratio. Figure 4 shows cases where the excess loss is 1.5, 2.0, and 2.5 dB. The horizontal axis indicates the number of wavelengths. For example, to use 32 or 40 wavelengths, the LD-AWG frequency offset must to be suppressed to 2030 GHz. The LD's frequency deviation is thought to be 50 GHz deduced from the standard deviation of the LD's emission wavelength being about 0.3 nm [5]. Considering the same amount for the AWG's frequency deviation, it is desirable to allow the LD-AWG frequency offset to be at least 100 GHz. This mitigates the wavelength accuracy requirement for optical devices and components, so it helps the economical efficiency of the system. From figure 4, we see that eight is critical as the number of wavelengths for excess loss of 1.5-2.5 dB at AWG. When the number of wavelengths is eight, i.e. the frequency spacing is 500 GHz, an LD-AWG frequency offset of 100-150 GHz is acceptable. However, for more wavelengths, it must be below 100 GHz. Therefore, OPTIMA-2 uses eight-wavelength optical WDM interconnection, the same as OPTIMA-1. The total switching capacity is thus 5.12 Tb/s.

**Fabrication of Optical Modules**

Figure 5 and 6 show the configurations of the WDM transmitter and receiver module, respectively. The interface speed of WDM transmitter and receiver modules needs to be more than 1.25 Gb/s, that is one eighth of 10 Gb/s, for the reasons already mentioned. We selected 2.5 Gb/s taking into account the availability of optical transmission ICs. Figure 5(a) and 6(a) show block diagrams of the WDM transmitter and receiver. The electrical interface of each 2.5-Gb/s channel is
demultiplexed to four 622-Mb/s signals. This eases the restrictions on printed circuit board (PCB) patterning. Thus, the WDM transmitter module has 4:1 multiplexer ICs and the WDM receiver module has 1:4 demultiplexer ICs with a clock data recovery function.

The optical interfaces of modules were fabricated very compactly using a silica-based planar lightwave circuit (PLC) platform, on which an AWG coupler or decoupler was formed. Furthermore, we used PLC hybrid integration, which enables optical devices to be flip-chip bonded onto an AWG [6]. We used spot-size converter integrated DFB LDs [7] and refracting-facet PDs [8]. They are electrically connected to the PLC platforms using Au/Sn solder. Figure 5(b) and 6(b) show the configurations of PLC platforms. LDs are connected via thin film solder in order to conduct the heat generated by LDs away to the PLC substrate. On the other hand, PDs are soldered using small bumps to minimize the parasitic capacitance.

Figure 5(c) and 6(c) show photographs of modules fabricated on PCBs. The 2.5 Gb/s electrical signals between optical devices and electrical circuits are transmitted via thin coaxial cables. We used a wiring substrate in order to mount termination resistors and pre-amplifiers close to the optical devices for the transmitter and receiver, respectively. The wiring substrate also provides pitch conversion between the PLC and coaxial connectors. All the optical devices on a PLC can be cooled together by one Peltier component integrated with a heat sink and attached on the rear of the PCB.

Waveforms of the WDM transmitter and pre-amplifier output are shown in figure 5 (d) and 6(d), respectively. The eye pattern obtained was fairly good. We examined the operation of these modules connected through the AWG wavelength router. Bit error rate measurements confirmed error-free operation. We also experimentally examined the operation of the inter-stage, optical WDM interconnection subsystem including the wavelength assigner and packet regenerator. Test data cells generated by a pulse pattern generator were transmitted through the wavelength assigner, optical WDM modules, and packet regenerator. The results show that cells were properly converted to their assigned wavelengths according to the
routing bit in their header. Therefore, we successfully confirmed the feasibility of a 5-Tb/s switching system.

Conclusions
We fabricated 8-wavelength 2.5-Gb/s WDM transmitter and receiver modules for a 5-Tb/s switching system. The number of wavelengths was chosen based on the design of the optical level diagram considering the wavelength deviation of optical devices and components. It contributes to economical efficiency by providing a loose restriction on wavelength accuracy. We used PLC hybrid integration technology to make the optical WDM modules compact. We experimentally demonstrated basic operations of intra-switch optical packet-by-packet switched interconnection. The results confirm the feasibility of a 5-Tb/s switching system.

References