# 640-Gb/s High-Speed ATM Switching System Based on 0.25-$\mu$m CMOS, MCM-C, and Optical WDM Interconnection

Naoaki Yamanaka, *Fellow, IEEE*, Ryusuke Kawano, *Member, IEEE*, Eiji Oki, *Member, IEEE*, Seisho Yasukawa, *Member, IEEE*, and Katsuhiko Okazaki

***Abstract*—A 640-Gb/s high-speed ATM switching system that is based on the technologies of advanced MCM-C, 0.25-$\mu$m CMOS, and optical wavelength-division-multiplexing (WDM) interconnection is fabricated for future broadband services. A 40-layer, 160 $\times$ 114 mm ceramic MCM forms the basic ATM switch module with 80-Gb/s throughput. It consists of an 8 advanced 0.25-$\mu$m CMOS LSIs and 32 I/O bipolar LSIs. The MCM has a 7-layer high-speed signal line structure having 50-$\Omega$ strip lines, high-speed signal lines, and 33 power supply layers formed using 50-$\mu$m very thin ceramic layers to achieve high capacity. A uniquely structured closed-loop-type liquid cooling system for the MCM is used to cope with its high-power dissipation of 230 W. A three-stage ATM switch is made using optical WDM interconnection between the high-performance MCMs. For WDM interconnection, newly developed compact 10-Gb/s, 8-WDM optical transmitter and receiver modules are used. These modules are each only 80 $\times$ 120 $\times$ 20 mm and they dissipate 9.65 W and 22.5 W, respectively. They have special chassis for cooling. The chassis contains high-performance heat-conductive plates and micro-fans. An optical WDM router based on an arrayed waveguide router is used for mesh interconnection of boards. The optical WDM interconnect has 640-Gb/s throughput and easy, simple interconnection. The system, MCM, and optical WDM interconnection will be applied to future broadband backbone networks.**

***Index Terms*—ATM, cooling system, multichip module, switching system, WDM interconnection.**

## I. Introduction

DEMAND is growing for a broadband backbone network that will handle high-speed digital communication services such as data, video, and high-definition TV [1]. For these services, an ATM switching system offering of throughput of several tens of Gb/s has been developed [2]. However, its operating speed must be increased as shown in Fig. 1. Fortunately, VLSI technologies have dramatically improved, so the next advance needed is an innovative packaging technology that can support devices capable of switching very-high-speed signals at speeds on the order of gigabits per second and that is cost effective [3]. The latest ATM switching system employs advanced VLSIs and multi-chip modules (MCMs) [4]–[8], and the latter is one of the keys to achieving new switching systems.

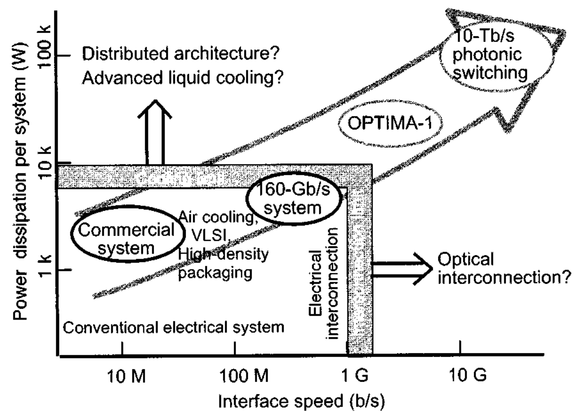


Fig. 1. Operating speed limits and key technologies.

In 1994, the fastest, fully electronic 160-Gb/s ATM switching system [3] used advanced 1.0-$\mu$m bipolar super-self-aligned (SST) technology and multi-layer Cu–polyimide MCMs [9], [10]. It used a 4-level packaging technique and included LSIs, MCMs, sub-boards, and a power supply frame. Four switching LSIs were integrated into one MCM by tape automated bonding (TAB). The MCM offered a 2 $\times$ 2 ATM crosspoint matrix connection with pipelining operation. Four Cu–polyimide MCMs were integrated on each sub-board and were interconnected using newly developed impedance controlled interconnect flexible printed circuit (FPC) connectors. All 64 MCM switching modules were mounted within the power supply frame. The system operation speed was limited to 160 Gb/s by the constraints of cooling (power supply) and interconnection.

VLSI technology continues to advance every year and switching system throughput may continue to be incrementally increased. However, there are some strong limitations. Fig. 1 shows that the factors limiting conventional electrical switching throughput to 160-Gb/s are cooling and interconnection. Advanced VLSI technologies, such as the quarter-micron CMOS, can integrate more than 2 million gates on one chip and can operate up to the Gb/s level. However, advanced ATM switching chips consume more than 10 W. The resulting heat load limits us to one chip if we use standard air cooling. Fig. 1

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N. Yamanaka and E. Oki were with the NTT Network Service Systems Laboratories, NTT Cooperation, Tokyo 180-8585, Japan, and they are now with the NTT Network Innovation Laboratories, Tokyo 180–8585, Japan (e-mail: yamanaka.naoaki@lab.ntt.co.jp; oki.eiji@lab.ntt.co.jp).

R. Kawano was with the NTT Network Service Systems Laboratories, NTT Cooperation, Tokyo 180-8585 Japan. He is now with NTT Electronics Corporation, Tokyo 180–8585, Japan (e-mail: kawano@atsu1.nel.co.jp).

S. Yasukawa and K. Okazaki are with the NTT Network Service Systems Laboratories, NTT Cooperation, Tokyo 180-8585, Japan (e-mail: yasukawa.seisho@lab.ntt.co.jp; okazaki.katsuhiko@lab.ntt.co.jp).

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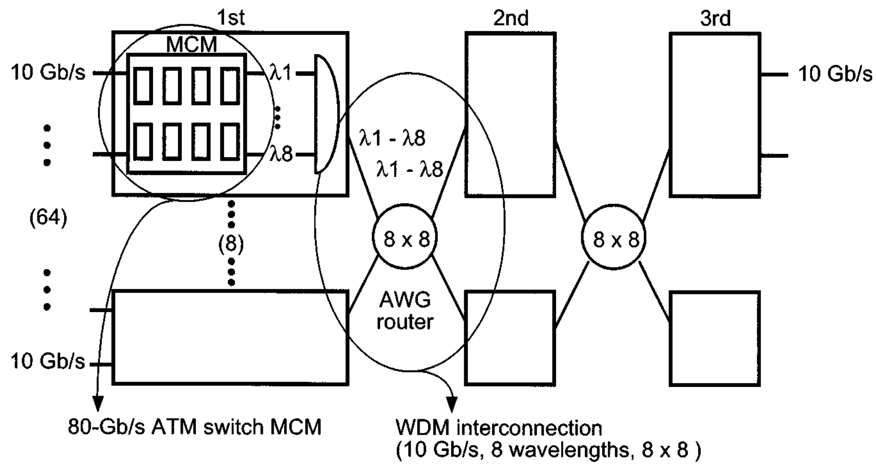


Fig. 2. Physical implementation of OPTIMA with 640-Gb/s throughput.

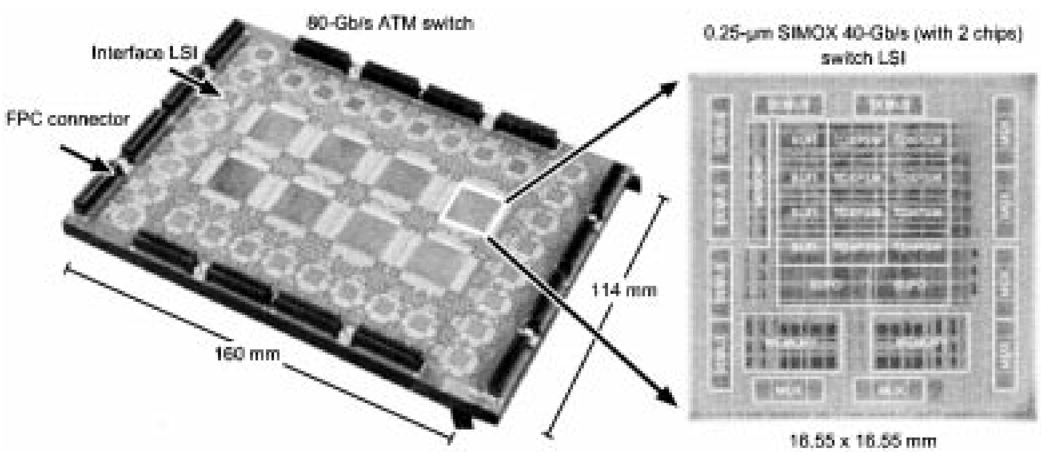


Fig. 3. The 80-Gb/s ATM switch MCM.

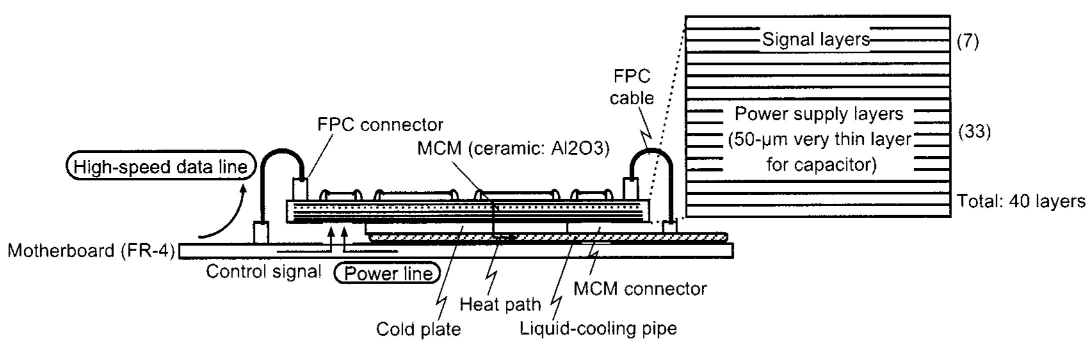


Fig. 4. Cross section of MCM-C.

indicates the cooling limit per system. Some sophisticated techniques can be used to offset these limits. The limits on electrical interconnection are mainly caused by loss, crosstalk, and reflection. On the other hand, the cooling limit is a combination of cooling capacity and power supply mechanism. Optical interconnection and distributed architectures are among the breakthroughs needed to overcome these limitations. In addition, sophisticated electrical systems are needed to achieve high-speed data interconnection in small areas. Obviously the power density level will continue to increase. Another limitation is the use of parallel electrical buses for interconnection. Such buses are not space efficient and do not support continued increases in the physical integration level because of their high levels of crosstalk.

Our ATM development strategies are also shown in Fig. 1. This paper describes key technologies for our newly developed 640-Gb/s throughput advanced ATM switching system, which is called an OPtically Interconnected Multistage ATM switch (OPTIMA). It is formed by the MCMs and optical wavelength-division-multiplexing (WDM) interconnections. The OPTIMA switching system employs 0.25-$\mu$m advanced CMOS technology [11], a 40-layer very-thin ceramic MCM, and

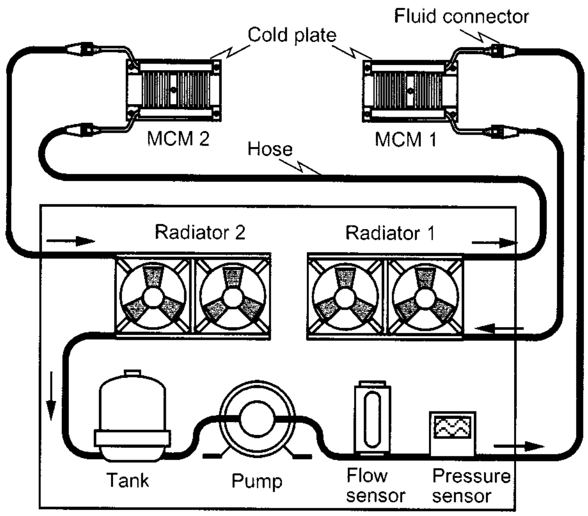


Fig. 5. Compact liquid-cooling system.

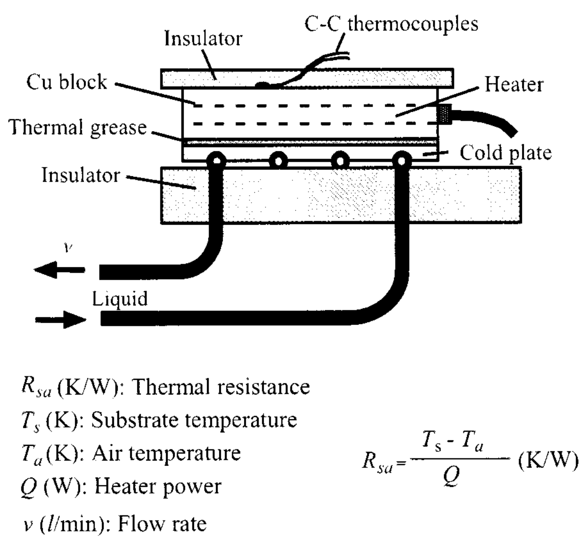


Fig. 6. Experimental setup of cooling system.

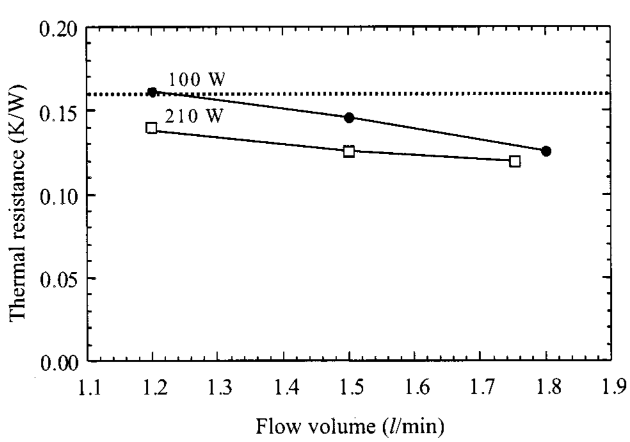


Fig. 7. Performance of cooling system.

optical WDM interconnection. By combining these advanced hardware technologies, we have successfully demonstrated a 640-/s throughput (the world's fastest) ATM switching system for future broadband backbone networks.

TABLE I
ROUTING CHANNEL TABLE OF AWG FILTER

| Output channels \ Input channels | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| 1 | λ1 | λ2 | λ3 | λ4 | λ5 | λ6 | λ7 | λ8 |
| 2 | λ2 | λ3 | λ4 | λ5 | λ6 | λ7 | λ8 | λ1 |
| 3 | λ3 | λ4 | λ5 | λ6 | λ7 | λ8 | λ1 | λ2 |
| 4 | λ4 | λ5 | λ6 | λ7 | λ8 | λ1 | λ2 | λ3 |
| 5 | λ5 | λ6 | λ7 | λ8 | λ1 | λ2 | λ3 | λ4 |
| 6 | λ6 | λ7 | λ8 | λ1 | λ2 | λ3 | λ4 | λ5 |
| 7 | λ7 | λ8 | λ1 | λ2 | λ3 | λ4 | λ5 | λ6 |
| 8 | λ8 | λ1 | λ2 | λ3 | λ4 | λ5 | λ6 | λ7 |

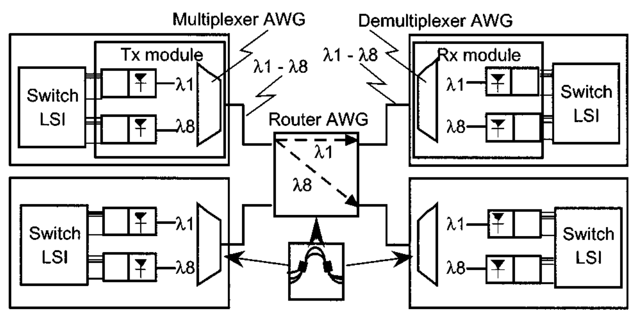


Fig. 8. Block diagram of optical wavelength division routing interconnection.

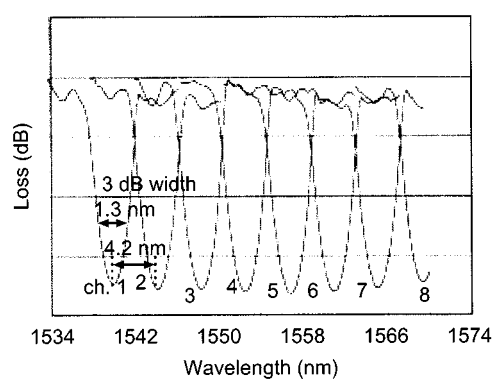


Fig. 9. Loss spectra of AWG filter.

## II. OVERVIEW OF 640-Gb/s ATM SWITCHING SYSTEM, OPTIMA

OPTIMA has a three-stage, optically interconnected ATM switching structure [12]. A three-stage switch architecture is attractive because of its scalability. A schematic of the physical implementation block of OPTIMA is shown in Fig. 2. The first-stage switches distribute all virtual connection routes randomly. This roughly equalizes the loads on the second-stage switches [13]. Since highly statistical large-capacity links are used, the loads on the second-stage switches are balanced.

The switching system consists of eight 80-Gb/s ATM switch MCMs and several optical WDM routers. For the optical WDM interconnection of switch MCMs, newly developed compact optical WDM transmitter (TX) and receiver (RX) modules are used with planar lightwave circuit (PLC). The 80-Gb/s ATM switch MCM is mounted on the motherboard and interconnected by the proposed optical WDM three-stage network.

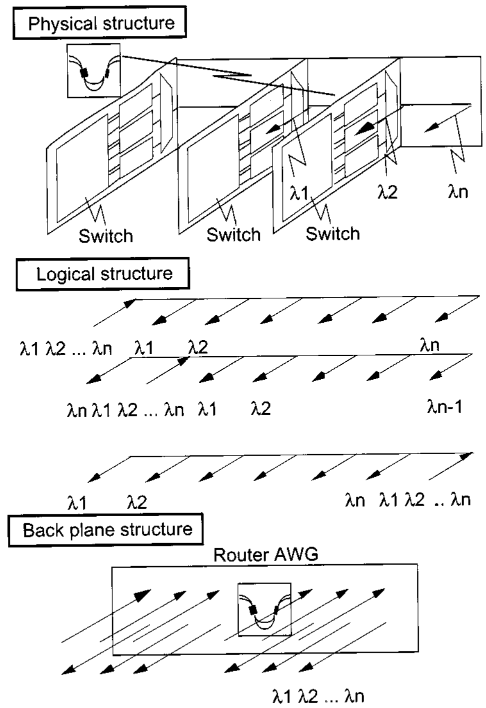


Fig. 10. System image of optical routing interconnection and optical addressing back-wired board.

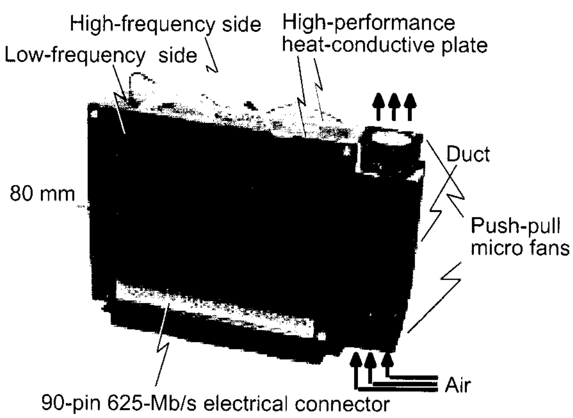


Fig. 11. External view of the module.

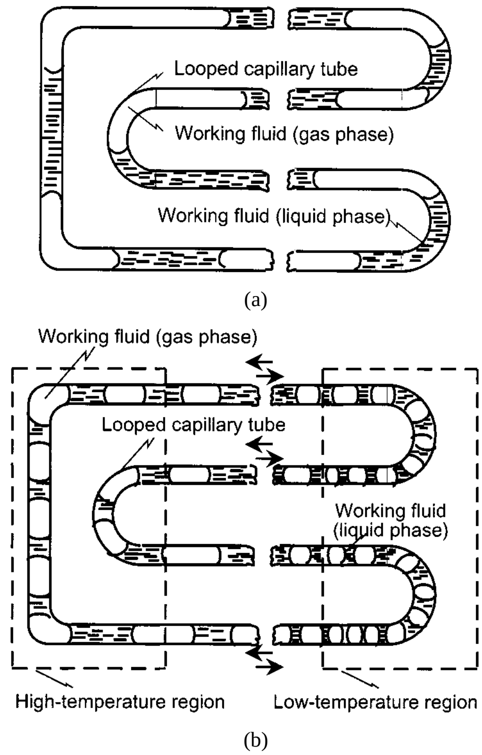


Fig. 12. Heat transfer mechanism.

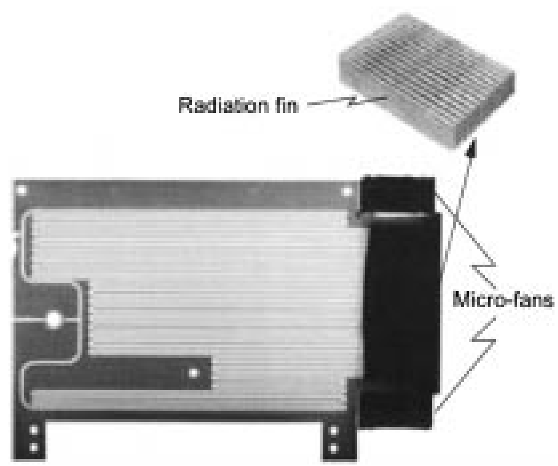


Fig. 13. X-ray photograph of the cooling structure.

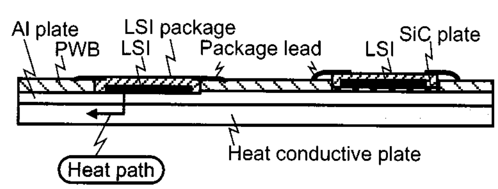


Fig. 14. Cross section of mounted chips.

## III. 80-Gb/s ATM Switch MCM

The 80-Gb/s ATM switch MCM is made using eight 0.25-$\mu$m advanced CMOS 4 $\times$ 2 switch LSIs and 32 Si-bipolar speed-converter LSIs [14]. This ATM switch constitutes an 8 $\times$ 8 matrix switch with 10-Gb/s links. Functional blocks of the switch LSI are labeled on the right side of Fig. 3. The switch LSI is 15.6 $\times$ 15.6 mm and has 250 kilogates and 176 Kb of RAM. Maximum operating speed is 1.25 Gb/s and power dissipation is approximately 7 W. Eight switch LSIs are mounted on the 40-layer ceramic MCM, also shown in Fig. 3. The speed-conversion LSIs around the switch LSIs change the signal speed from 625 Mb/s to 1.25 Gb/s and vice versa. Interconnection inside the MCM is 1.25 Gb/s pseudo ECL [11], [14] and 625-Mb/s ECL is used between MCMs. There are 1024 625-Mb/s MCM I/O lines. The MCM size is 114 $\times$ 160 mm.

Its cross section is shown in Fig. 4. Newly developed high-power stacking-type connectors are used and a uniquely structured, closed-loop-type liquid cooling system is used to cope with the MCMs power dissipation of 230 W. The MCM has a 7-layer high-speed signal line structure having 50-$\Omega$ strip lines, high-speed signal lines, and 33 power supply layers formed using 50-$\mu$m very thin ceramic layers to achieve high capacity. In addition, it includes a total of 1300 termination resistors made by the thin film technique.

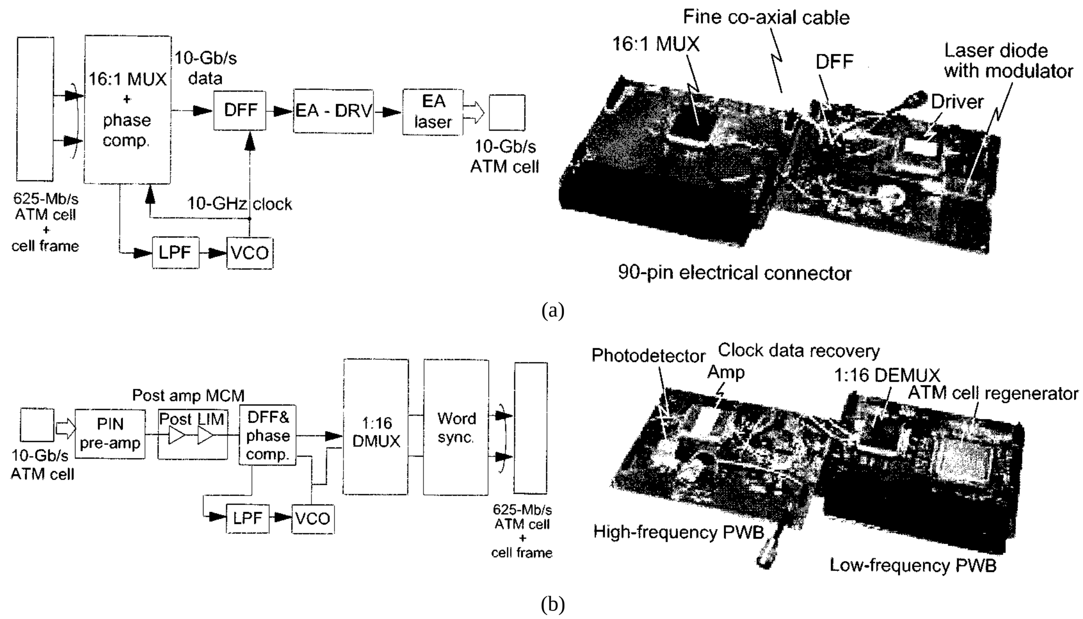


Fig. 15. Internal views of TX and RX.

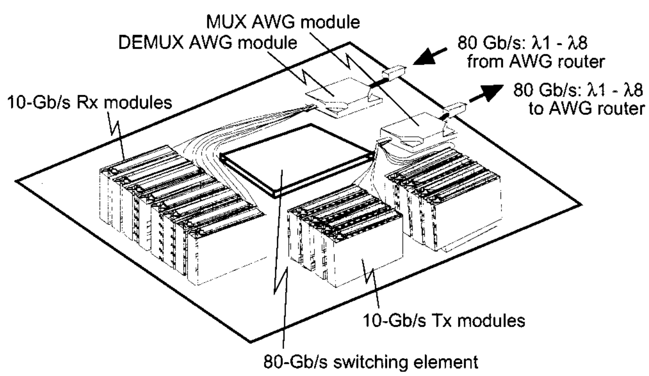


Fig. 16. Arrangement of modules in the unit.

A cold plate is mounted on the back of the MCM and a compact liquid-cooling system, shown in Fig. 5 [15], is used. This system consists of cooling plates, hoses for the coolant, two valve connectors, a pump, and radiators. Each radiator has two cooling elements (thermal resistance 0.09 K/W), which are connected in parallel using high-performance heat pipes. These elements are forced-air cooled. The heat comes into contact with the radiators through the cooling plates. The coolant, which is pressurized to 4-8 kg/cm$^2$ by the pump, is cooled by radiator 1 after passing the cooling plate of MCM 1. It continues on and passes the cooling plate of MCM 2, then returns to the pump. The MCM is connected to the printed wiring board (PWB) by stack-type connectors [16]. The cooling plate touches the backside of the MCM. It is 150 $\times$ 95 $\times$ 8 mm.

We fixed a heater to the cooling plate and measured the plate's temperature at various flow rates. We estimated that if the MCM power is 230 W and the maximum allowable chip junction temperature is 363 K, the thermal resistance between chip junction and cold plate should be less than 0.16 K/W. Fig. 6 shows the experiment setup of the cooling system. Fig. 7 shows the performance of the cooling system, in particular the flow volume versus the thermal resistance between the cold-plate and air. In our experiments, the thermal resistance was less than 0.16 K/W at 210 W. Therefore, we can achieve high-performance compact liquid cooling for high-power switch MCMs that dissipate over 200 W.

## IV. WDM Interconnection

### A. Optical Interconnection

Another important technique used in OPTIMA is optical WDM routing [17]. The basic block diagram of optical WDM interconnection is shown in Fig. 8. WDM interconnection consists of eight 10-Gb/s optical TX modules with different wavelengths, 8 $\times$ 8 optical arrayed wave guide (AWG) filter routers [18] and eight 10-Gb/s optical RX modules.

Each 80-Gb/s switch processes eight wavelength signals, each carrying 10 Gb/s. The router AWG performs wavelength routing as shown in Table I. The input WDM channels ($\lambda1$ to $\lambda8$) from the first port are switched as follows: $\lambda1$ to output port #1, $\lambda2$ to port #2 ... $\lambda8$ to port #8. On the other hand, the input WDM channels ($\lambda1$ to $\lambda8$) from the second input port are switched as follows: $\lambda1$ to output port #2, $\lambda2$ to port #3 ... and $\lambda8$ to port #1 as in a cyclic shift register. Each output port handles eight WDM channels ($\lambda1$ to $\lambda8$) where each channel comes from a different input port. In other words, all 80-Gb/s ATM switches are interconnected by different wavelengths.

The frequencies of the lasers in TX modules shown in Fig. 8 change strongly with temperature. The laser devices shift their center frequencies by 12.5 GHz/K. The passband (3 dB) of most AWGs is about 30% of their channel spacing. The channel spacing of a conventional AWG for a long-haul optical transmission system is about 100 GHz [19]. Therefore, the passband of the conventional AWG is only 30 GHz. This requires a complex temperature control circuit, which complicates system design. To give the system a wide temperature margin and eliminate complex temperature control circuits, we used an AWG with a wide channel spacing of 525 GHz (centered at

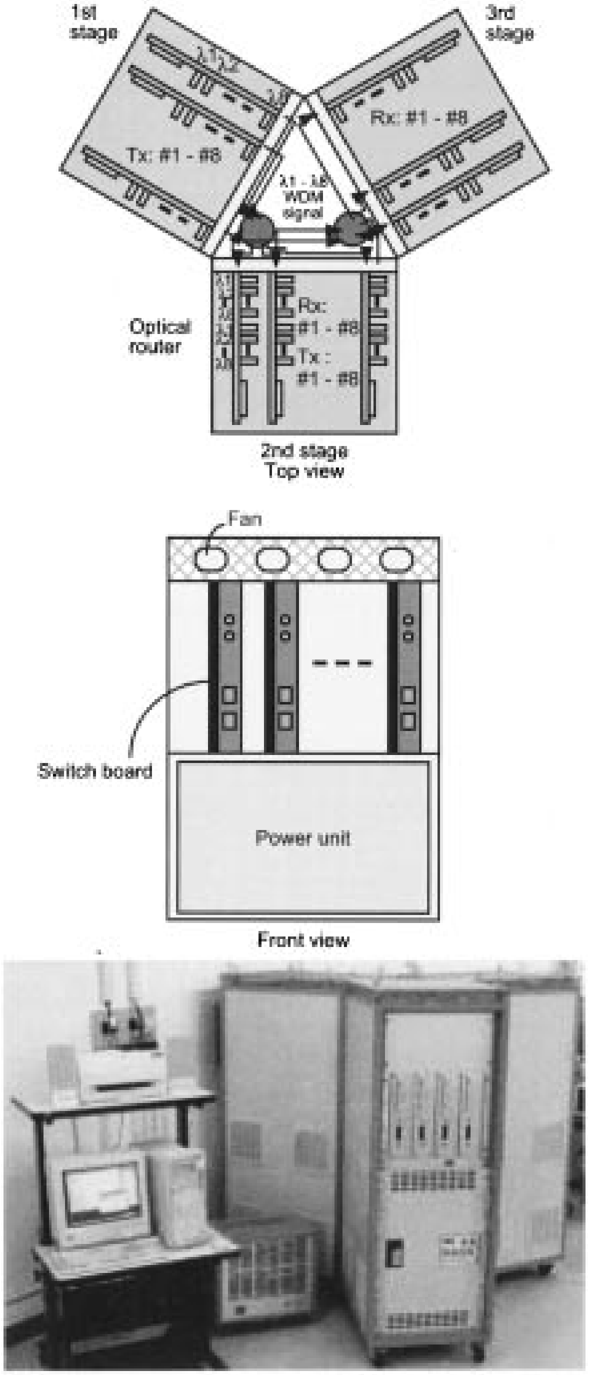


Fig. 17. Schematic diagram of 640-Gb/s ATM switching system.

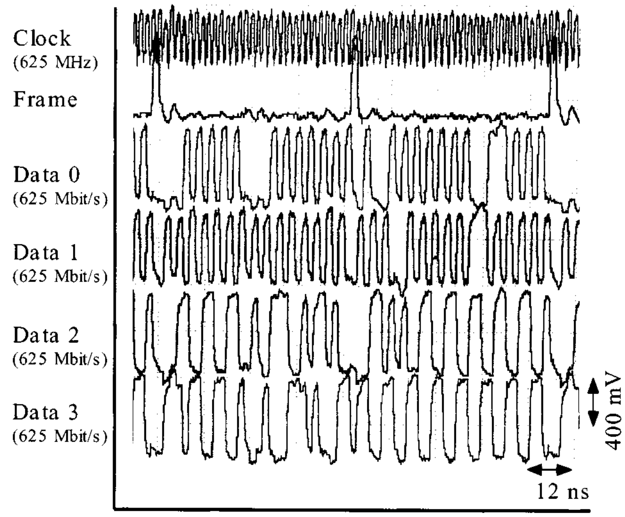


Fig. 18. 625-Gb/s waveform of switch MCM.

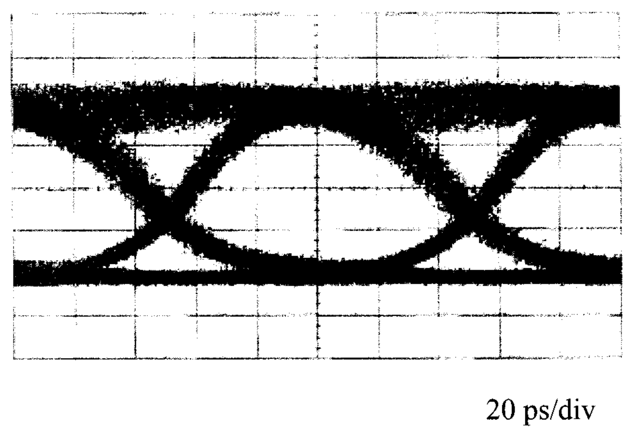


Fig. 19. 10-Gb/s waveform of TX module.

1555.2 nm). Fig. 9 shows its loss spectra. This AWG has a wider passband (160 GHz, 1.3 nm) than the conventional AWG (30 GHz, 0.24 nm), so this system can handle a temperature range about five times wider than the conventional system. This wide channel spacing relaxes the temperature constraints placed on the lasers. As a result, the total system size is dramatically reduced.

The 640-Gb/s system is implemented as an AWG back-wired board. The system, called the optical wavelength addressing back-wired board, is shown in Fig. 10. A WDM signal is sent from the switch board, and the AWG switches each signal in a cyclic shift register manner as described above. All first-stage switch boards are interconnected to the second-stage switch boards.

### B. Module Structure and Heat Transfer Device

The very compact 10-Gb/s, 8-wavelength TX/RX module for WDM interconnection is shown in Fig. 11. It has a special chassis for cooling. Instead of conventional radiation fins, high-performance heat-conductive plates are used to conduct heat from sources, such as the lasers, to fins inside the duct on the end of the module, where it is dispersed by push–pull micro-fans.

The structure of a closed-loop-type heat pipe in the high-performance heat-conductive plates is shown in Fig. 12. HFC134a ($CH_2FCF_3$), which is environmentally acceptable, is used as the fluid. As heating and cooling are applied to the two ends, vapor is generated in the heating section and condenses to a liquid in the cooling section. The volume expansion due to the vaporization and contraction due to the condensation cause an oscillating motion of the fluid that sends vapor to the condenser and returns liquid to the vaporator. The oscillatory motion of the liquid and vapor slugs is self-sustaining as long as the heating and cooling conditions are maintained [20], [21].

There are many heat pipe technologies for cooling electronics, for example [21] and [22]. We selected the high-performance heat-conductive plate for the TX and RX modules because the plates are available at any position with little gravity effect, which eliminates design restrictions and enables the plates to have a simple construction.

An x-ray photograph of the cooling structure is shown in Fig. 13. To avoid x-rays penetrating the overlapping low- and high-frequency sides, one side plate was removed to take the photograph. The looped capillary tube is contained in an aluminum plate 2 mm thick as shown in Fig. 14. This cooling structure is compact but can handle high heat loads. The TX and RX modules are each only 125 $\times$ 85 $\times$ 23 mm.

The TX and RX modules consist of high-frequency PWBs and low-frequency PWBs. They are arranged face-to-face and connected with fine co-axial cables. Instead of conventional radiation fins, a high-performance heat-transfer device is used to conduct heat from sources, such as the lasers, to fins inside the duct on the end of the module, where it is dispersed by push–pull micro-fans. Photographs of the RX module's internal view excluding the cooling structure are shown in Fig. 15 together with a functional block diagram. The main elements of the TX are an integrated light source with a multiple-quantum well distributed feedback laser, an electro-absorption modulator with a Peltier device for fine temperature control, and a 16 : 1 MUX. In the WDM system, wavelength stability is critical because the system utilizes differences in wavelength. As the wavelength characteristics are sensitive to temperature, adequate temperature control is necessary. The power dissipation of the TX is 9.65 W including the Peltier device. The laser diode with the Peltier device is in contact with the heat-conductive plate and the heat generated by the laser diode including the Peltier device is also radiated. The main elements of the RX are a clock data recovery circuit, a 16 : 1 DEMUX, and a word synchronization LSI for ATM cell regeneration. The power dissipation of the RX is 22.5 W.

## V. Experiments

In OPTIMA, an 80-Gb/s switch MCM and optical WDM interconnection are mounted on one PWB. One board contains 8 TXs and 8 RXs (each 10 Gb/s) in addition to the 80-Gb/s ATM switching element, as shown in Fig. 16. For 640-Gb/s interconnection, we need 64 TXs and 64 RXs, so it is important to reduce their size and pack them closely together. We made compact modules by introducing a novel cooling structure.

The OPTIMA 3-stage ATM switch network was subjected to initial tests. An overview of the three-stage OPTIMA switch is shown in Fig. 17. We evaluated the switch performance by using pulse pattern generators (PPGs) and error rate detectors (BEDs). Input cells at an input port were generated at a PPG so they could be routed to multiple output ports, where output signals were monitored by a BED. The payload of input cells was set to be fixed patterns and random patterns. Fig. 18 shows the measured waveform examples of the switch MCM at 622 Mb/s. Fig. 19 shows the measured waveform of the TX module under 10 Gb/s operation. The output power of the laser was 3.72 dBm. The laser unit operation was stable in terms of output laser power and wavelength. We confirmed that the bit error rate of the three-stage switch was less than $10^{-12}$ at the speed of 10 Gb/s.

## VI. Conclusions

A 640-Gb/s very advanced ATM switching system using 0.25-$\mu$m CMOS VLSIs, 40-layer ceramic MCMs and 10-Gb/s, 8-wavelength 8 $\times$ 8 optical WDM interconnection has been fabricated. The 80-Gb/s MCM integrates 8 VLSI chips and a 50-$\mu$m very thin power supply layer ceramic substrate with 40 layers is used. In addition, an innovative high-performance closed-loop-type liquid cooling technique is used. To breakthrough the interconnection bottleneck, optical WDM interconnection is used. It has 10-Gb/s 8-wavelength 8 $\times$ 8 interconnection capability. It achieves 640-Gb/s interconnection within a very small size. Preliminary tests show that these 80-Gb/s ATM switch MCM and optical WDM interconnection technologies can be applied to future high-speed broadband networks.

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**Naoaki Yamanaka** (F'00) received the B.E., M.E., and Ph.D. degrees in engineering from Keio University, Japan, in 1981, 1983, and 1991, respectively.

In 1983, he joined Nippon Telegraph and Telephone Corporation's (NTTs) Communication Switching Laboratories, Tokyo, Japan, where he was engaged in research and development of a high-speed switching system and high-speed switching technologies for broadband ISDN services. Since 1994, he has been active in the development of ATM base backbone network and system including Tb/s electrical/optical backbone switching as NTT's Distinguished Technical Member. He is now researching future optical IP network, and optical MPLS router system. He is currently a Senior Research Engineer, Supervisor, and Research Group Leader in the Network Innovation Laboratories, NTT. He has published over 112 peer-reviewed journal and transaction articles, written 82 international conference papers, and been awarded 174 patents including 17 international patents.

Dr. Yamanaka received Best of Conference Awards from the 40th, 44th, and 48th IEEE Electronic Components and Technology Conferences in 1990, 1994, and 1998, the TELECOM System Technology Prize from the Telecommunications Advancement Foundation in 1994, the IEEE CPMT Transactions Part B: Best Transactions Paper Award in 1996, and the IEICE Transaction Paper Award in 1999. He is Technical Editor of the *IEEE Communication Magazine*, Broadband Network Area Editor of *IEEE Communication Surveys*, Editor of IEICE TRANSACTIONS as well as TAC Chair of Asia Pacific Board at IEEE Communications Society. He is a member of the IEICE.

**Ryusuke Kawano** (M'98) was born in Oita, Japan on April 2, 1964. He received the B.E. and M.E. degrees from the University of Osaka, Japan, in 1987 and 1989, respectively.

In 1989, he joined Nippon Telegraph and Telephone Corporation (NTT), Tokyo, Japan, and began researching and developing process technology for high-speed Si-bipolar devices. Since 1992, he has been engaged in R&D on high-speed integrated circuits using Si bipolar transistors and GaAs MESFETs at the NTT LSI Laboratories, Kanagawa, Japan. Since moving to NTT Network Service Systems Laboratories, Tokyo, in 1997, he engaged in very-large-capacity ATM switching hardware. He moved to NTT Electronis Corporation in 1999. His current job is a Designer of ultra-high-speed modules.

**Eiji Oki** (M'95) received the B.E. and M.E. degrees in instrumentation engineering and the Ph.D. degree in electrical engineering from Keio University, Yokohama, Japan, in 1991, 1993, and 1999, respectively.

In 1993, he joined Nippon Telegraph and Telephone Corporation's (NTT's) Communication Switching Laboratories, Tokyo, Japan. He has been researching multimedia-communication network architectures based on ATM techniques, traffic-control methods, and high-speed switching systems in NTT Network Service Systems Laboratories. He was a Visiting Scholar at Polytechnic University, Brooklyn, NY, from 2000 to 2001. He is now engaged in researching and developing high-speed optical IP backbone networks as a Research Engineer with NTT Network Innovation Laboratories. He coauthored *Broadband Packet Switching Technologies* (New York: Wiley, 2001).

Dr. Oki received the Switching System Research Award and the Excellent Paper Award from the IEICE in 1998 and 1999, respectively. He is a member of the IEICE.

**Seisho Yasukawa** (M'99) received the B.E. and M.E. degrees from the University of Tokyo, Tokyo, Japan, in 1993 and 1995, respectively.

In 1995, he joined Nippon Telegraph and Telephone Corporation's (NTT's) Network Service Systems Laboratories, Tokyo. He is currently researching future multimedia communication network architecture based on MPLS technology and QoS control issues of mobile IP network at NTT Network Service Systems Laboratories as a Research Engineer.

Mr. Yasukawa received the IEICE Switching System Research Award, and the IEICE Academic Research Award, in 1998 and 2001, respectively. He is a member of IEEE Communication Society.

**Katsuhiko Okazaki** was born in Tokyo, Japan, on November 27, 1969. He received the B.E. and M.E. degrees from the University of Electrocommunications, Japan, in 1993 and 1995, respectively.

In 1995, he joined Nippon Telegraph and Telephone Corporation's (NTT's) Network Service Systems Laboratories, Tokyo, Japan. He has been researching high-speed and high-density packaging technologies for large capacity ATM switching systems. He is currently developing broadband content delivery service systems.

Mr. Okazaki is a member of the IEICE of Japan.