Multilane Photonic Spectral Processor Integrated in a Spatial and Planar Optical Circuit for a Space-Division Multiplexing Network

Mitsumasa Nakajima ( †, Member, IEEE, Kenya Suzuki ( †, Member, IEEE, Keita Yamaguchi, Hirotaka Ono ( †, Senior Member, IEEE, Senior Member, OSA, Takashi Goh, Member, IEEE, Mitsunori Fukutoku, Yutaka Miyamoto, Member, IEEE, and Toshikazu Hashimoto

Abstract—We developed a multilane photonic spectral processor array integrated with a spatial and planar optical circuit platform. This device enables individual control of the optical power in the spatial and wavelength domains by controlling the phase pattern on liquid crystal on a silicon spatial light modulator and the heater electricity of a waveguide-based variable attenuator. We constructed a prototype device including an array of seven spectral processors. We transmitted 100-Gbps DP-QPSK signals over seven spans with a small optical-signal-to-noise ratio penalty of 0.05 dB, which suggests that the device can work in actual networks. As an application, we demonstrated gain equalizing of a multicore erbium-doped fiber amplifier (MC-EDFA). The device equalized the gain spectra of the MC-EDFA to an accuracy of ±0.8 dB over 30 nm.

Index Terms—Integrated optics, optical waveguides, space division multiplexing, spatial light modulators, wavelength division multiplexing.

I. INTRODUCTION

THE rapid increase in network traffic driven by, for example, video streaming services and the internet of things requires an extremely high transmission capacity for optical networks. Recent advances in wavelength division multiplexed (WDM) fiber-optic transmission technology have so far kept up with the rapid increase in network traffic [1], [2]. However, we are fast approaching the limits of capacity of single-mode fiber and growth of conventional WDM networks because of the nonlinear Shannon limit [3], [4]. A potential solution to this problem is spatial division multiplexing (SDM) transmission over multicore fibers (MCFs) and/or few-mode fibers (FMFs) [5], [6]. Recent experimental demonstrations of SDM transmission have clearly shown that SDM is very promising for future backbone networks with ultra-high capacity [7]–[10]. For making SDM viable in real long-haul networks, the SDM-compatible photonic spectral processor is a key device [11]. It can individually control the optical power in each wavelength and spatial channel and be used for power balancing of the amplified power spectra, wavelength blocking of the input signals, optical performance monitoring, and pulse shaping of transmitted signals for every spatial channel [12]–[17]. Especially, SDM-compatible dynamic gain equalizers are important components because the gain of multicore erbium-doped fiber amplifiers (MC-EDFAs) typically exhibits significant core and wavelength dependency.

N. K. Fontaine et al. first demonstrated such spectral processor arrays for this device; they were composed of free-space optics with an MCF frontend and liquid crystal on silicon spatial light modulator (LCOS-SLM) [12]. The MCF was rotated so that signals from MCF cores could be distinguished on the LCOS-SLM. However, their architecture is only usable for a few SDM channels because the signals from the adjacent cores would overlap on the LCOS plane. In addition, the power control of the spatial and wavelength channels has to be performed by only LCOS. This results in poor equalizing accuracy at a high attenuation (ATT) because the optical power is sensitive to the displayed phase on the LCOS.

Recently, we reported a spatial and planar optical circuit (SPOC) technique that combines waveguides and free-space optics [13], [15], [18]–[24]. This technique is suitable for spectral processors because the SPOC can potentially deal with a large number of SDM channels. In this paper, we describe a photonic spectral processor array using a SPOC platform. The device includes an array of seven spectral processors. In addition, it can control the spatial channel by using a variable optical attenuator (VOA) integrated into the waveguide frontend. As an application, we demonstrated gain equalizing of MC-EDFA.

Manuscript received June 30, 2017; revised August 22, 2017; accepted August 28, 2017. Date of publication September 10, 2017; date of current version February 24, 2018. This work was supported in part by the R&D project on “Research and Development of Space-Division Multiplexing Photonic Node” of the National Institute of Information and Communications Technology. (Corresponding author: Mitsumasa Nakajima.)

M. Nakajima, K. Suzuki, K. Yamaguchi, H. Ono, T. Goh, and T. Hashimoto are with NTT Device Technology Laboratories, NTT Corporation, Atsugi 243-0198, Japan (e-mail: nakajima.mitsumasa@lab.ntt.co.jp; x.kenya@lab.ntt.co.jp; yamaguchi.keita@lab.ntt.co.jp; ono.hirotaka@lab.ntt.co.jp; goh.takashi@lab.ntt.co.jp; hashimoto.toshikazu@lab.ntt.co.jp).

M. Fukutoku and Y. Miyamoto are with NTT Network Innovation Laboratories, NTT Corporation, Yokosuka 239-0847, Japan (e-mail: fukutoku.mitsunori@lab.ntt.co.jp; miyamoto.yutaka@lab.ntt.co.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2017.2748599

0733-8724 © 2017 IEEE. Translations and content mining are permitted for academic research only. Personal use is also permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.
The device flattened the gain spectra of the MC-EDFA to an accuracy of $\pm 0.8$ dB over 30 nm.

II. DEVICE STRUCTURE

A. Spatial Beam Transformer

The key component for multiplexing multiple photonic spectral processors is a waveguide-based optical frontend that includes spatial beam transformer (SBT) circuit elements. The SBT acts as a beam launcher. Fig. 1(a) shows its structure consisting of input/output (I/O) waveguides, a slab waveguide, and arrayed waveguides. The SBT functions as a cylindrical microlens integrated in a waveguide. It also works as an anamorphic prism. It has basically the same circuit structure as an arrayed waveguide grating (AWG), except that the path length difference of the arrayed waveguides is set at zero. It therefore does not disperse the light spectrally but forms an output beam profile. The output angle from the chip facet ($\theta_{SBT}$) is expressed as

$$
\theta_{SBT} = \frac{d_1}{d_2} \frac{p}{f_{SBT}},
$$

where $d_1$ and $d_2$ are the periods of the arrayed waveguides at the junction of the slab waveguide and the chip facet, $p$ is the offset position of the input waveguide from the center of slab waveguide, and $f_{SBT}$ is the focal length of the slab waveguide. The output beam radius $\omega_{SBT}$ is expressed as

$$
\omega_{SBT} = \frac{f_{SBT} \lambda}{\pi n \omega_0} \frac{d_2}{d_1},
$$

where $\lambda$ is the optical signal wavelength in vacuum, $n$ is the effective refractive index of the slab waveguide, and $\omega_0$ is the beam radius of the eigen mode of the input waveguide.

Basically, there are two possible ways of multiplexing spectral processors by using the SBT. One is the shared SBT as shown in Fig. 1(b). This way can reduce the chip size because it shares the SBT circuits. Although this feature enables us to integrate wavelength selective switches (WSSs) [18], [20]–[23], the non-uniformity of the wavefront in the SBT circuit directly causes optical coupling to unwanted ports. Therefore, the shared SBT intrinsically suffers from inter sub-processor lane crosstalk (XT). The other way is the individual SBT as shown in Fig. 1(c). This type is not suitable for integrating devices that have many I/O ports, such as WSSs, because it does not share the SBT. On the other hand, it potentially has small inter-lane XT thanks to the separated SBT structure. In the case of SDM-spectral processors, we need only $2 \times M$ I/O ports, where $M$ is the number of spatial channels, much less than in the WSS case. Therefore, we decided to use the individual SBTs in this study.

B. Configuration of Multilane Spectral Processors

Fig. 2(a) shows an explanatory schematic of the proposed spectral processor array using a SPOC platform. For simplicity, the number of spatial channels ($M$) is set to three in the figure. The device consists of a waveguide frontend with an SBT-based collimator array, a dispersion grating, lenses, and an LCOS-based SLM. Fig. 2(b) and (c) show the lane-multiplexing ($y$-$z$) and dispersion ($x$-$z$) planes of the optics. The $p$ values of the waveguide differ for each lane, which gives rise to the different output beam angles from the I/O SBTs. Because LCOS is polarization dependent, we put polarization diversity optics (a polarization beam splitter, PBS, and a half-wave plate, HWP) between the collimating lens and the grating. By considering simple 2-$f$ Fourier optics, the beam radius $\omega_{LCOS}$, and the beam position $d_{LCOS}$ on the LCOS can be described as follows under the small angle approximation:

$$
\omega_{LCOS} = \frac{f_o \lambda}{\pi \omega_{SBT}},
$$

$$
d_{LCOS} = f_o \sin(\theta_{SBT})
\approx f_o \frac{d_1}{d_2} \frac{p}{f_{SBT}},
$$

where $f_o$ is the focal length of the lens. As the $p$ values differ for each input port, the beam position can be separated on the LCOS-SLM plane. Therefore, input signals coming from the different cores in the input MCF are focused by the Fourier lens onto different areas of the LCOS-SLM plane in the $y$-direction because the signals are output to different directions from the waveguide frontend. Thus, each signal from the input MCF can be handled separately. Each one is steered by encoding a wavefront using the LCOS-SLM in order to couple it to output ports. Thus, we can shape the output spectra by setting a different phase slope for each wavelength channel ($x$-direction). The inter-lane XT of this device can be estimated by considering Gaussian beam propagation as follows,

$$
XT = \exp \left\{ - \left[ \left( \frac{\Delta \theta_{SBT}}{\omega_{SBT}} \right)^2 + \left( \frac{\Delta d_{LCOS}}{\omega_{LCOS}} \right)^2 \right] \right\},
$$
where $\Delta d_{\text{SBT}}$ is the distance between the adjacent I/O ports on the SBT, and $\Delta d_{\text{LCOS}}$ is the distance between the adjacent beams on the LCOS plane. As the inter-lane XT of the shared SBT is determined only by the second term in (5), i.e., $\text{XT} = \exp[-(\Delta d_{\text{LCOS}}/\omega_{\text{LCOS}})^2]$, the inter-lane XT of this device is intrinsically smaller than that of previous SPOC optics [18], [21].

Mach-Zehnder-interferometer-based variable optical attenuators (MZI-VOAs) [25] are integrated on each lane of the equalizers in the waveguide frontend; each one acts as a non-wavelength dependent attenuator. The MZI-VOAs are driven by electrical heaters using the thermo-optic effect. For gain equalization of MC-EDFA, the equalization of the wavelengths is performed by the LCOS-SLM, while the equalization of the spatial channels is achieved with the MZI-VOAs. This arrangement improves equalization accuracy because the MZI-VOA relaxes the attenuation requirement for the LCOS-SLM, whose accuracy gets worse as the attenuation level increases. The power equalization for the spatial channels is controlled with a single knob. This makes the level control of the spatial channels quite simple. Note that two MZI-VOAs are connected as in the inset in Fig. 3(c) in order to obtain a high extinction ratio. A similar functionality could be achieved using collimating lens array, as in previous studies on $M \times M$ wavelength cross connects [26], [27]. However, the optics need extra beam expanders, collimating lens array, and an external arrayed VOA, at least. On the other hand, in our architecture, these functions are smartly integrated in the waveguide frontend. In addition, we can potentially integrate more functions such as polarization diversity and fan-in/fan-out from multicore fiber [23], [24]. These features reduce the number of optical elements, which contributes to reducing the footprint and cost of the devices.

III. FABRICATION AND DEVICE CHARACTERISTICS

A. Waveguide Characteristics

We fabricated a prototype waveguide frontend for an array of seven spectral processors. The waveguide frontend was fabricated by using a conventional silica-based waveguide with an index contrast of 1.5%. The chip size was 72 mm $\times$ 28 mm. Fourteen arrayed SBTs and seven arrayed VOAs were integrated in the chip. We launched light into the I/O SBTs and measured the beam profiles by sweeping a slit beam profiler. Fig. 3(a) shows the measured output beam angles of the SBT as a function of input lane number. The output angle matched the designed value. The deviation from the designed line was within...
± 0.05°. Fig. 3(b) shows the normalized diffraction intensities of the first-order diffraction as a function of lane number. As shown in this figure, the diffraction efficiency was almost uniform, and the lane dependency was less than 0.3 dB. The output ports had an excess loss of about 1.25 dB because of the MZI-VOA. As the SBTs acted as a linear phased array system, there were some high-order diffractions like grating lobes of an arrayed antenna. However, their powers were much smaller than those of the main beams. In addition, they were focused on the outer region on the LCOS and were steered by the LCOS so that they did not couple with the output ports. Therefore, these diffractions did not degrade the XT characteristics. Fig. 3(c) shows the normalized insertion loss (IL) at 1550 nm as a function of heater power. In this experiment, only the MZI-VOA for core 2 was actuated. As can be seen, the optical power could be independently tuned with an extinction ratio of about 50 dB.

### B. Optical Bench-Top Characteristics

By using the fabricated waveguide frontend chip, we constructed an optical bench-top of the array of seven spectral processors. Fig. 4(a) shows the IL of the fabricated optical bench-top. The IL ranged from 6.6 to 9.4 dB over the C-band, which can be broken down into the waveguide loss of 2.8 dB (including the MZI-VOA loss of 1.25 dB), the grating loss of 2.5 dB, the LCOS loss of 0.8 dB, the free space optics loss of 0.2 dB (including the polarization beam splitter loss), and the alignment loss of 0.2 to 3 dB. By using an optimum grating, we could reduce the IL to about 5 dB. Fig. 4(b) shows the sub-processor lane dependency of IL and worst XT over the C-band. For comparison, the XT of a shared SBT is also plotted [21]. Here, the IL and XT were almost independent of the lane number, thanks to the uniform characteristics of the waveguide. In addition, as expected, the worst XT was much less than in the shared SBT case, suggesting the individual SBT arrangement is suitable for spectral processor applications. Fig. 5(a) shows the polarization dependent loss (PDL) measured at 1550 nm as a function of the lane number. The PDL values of the inner lane were good (less than 0.25 dB), but the PDLs became worse toward the outer lane. This degradation is considered to be due to misalignment of the y-z plane. Fig. 5(b) shows the PDL for the inner (lane 2), center (lane 4), and outer lane (lane 6) over the C-band. The PDL showed not only lane dependency, but...
also wavelength dependency; the worst PDL was 0.85 dB. This wavelength dependency was mainly due to misalignment of the free-space-optics on the x-z plane. We expect that the PDL can be reduced to less than 0.4 dB by optimizing the alignment.

Next, we examined the spectral processing characteristics of the constructed device. Fig. 6(a)–(g) show the transmission spectra of the outputs in sub-processor lanes 1 to 7. We set the LCOS phase pattern so that lanes 1 to 3 filtered with different passband widths of 50, 100, 150, and 200 GHz [Fig. 6(a)–(c)], lanes 5 to 7 made a flat passband [Fig. 6(d)–(f)], and lane 4 made a saw-tooth and sinusoidal spectral passband [Fig. 6(g)].

We also set the attenuation levels of the output signals to 0, 5, 10, and 15 dB by varying the power consumption of the MZI-VOAs. As shown in Fig. 6(a)–(c) and (g), the spectral processor function was successfully realized. In addition, the levels of the transmission spectra could be tuned with the MZI-VOAs while maintaining their spectral shape. Although the MZI-VOAs have slight wavelength dependency at the deep attenuation level, we could obtain a flat wavelength dependency of \(<\pm 0.8\) dB over the attenuation level of 0 to 15 dB. This means that the device can control the optical power of spatial and wavelength channels independently. Fig. 6(h) shows a typical filtered transmission and polarization dependent loss (PDL) spectrum of the device. The central wavelength of the filter was set at 1550 nm. The 0.5-dB transmission bandwidth was 32 GHz with a 50-GHz channel spacing. The PDL was 0.2 dB near the center frequency.

C. Transmission Characteristics

To confirm that our device is applicable to SDM networks, we transmitted a 100-Gbps DP-QPSK signal with 28-G baud rate through the device. We tried two experimental setups, as
shown in Figs. 7(a) and 8(a). In the first experiment [Fig. 7(a)], the modulated signal was split into seven components with an optical splitter. Each signal component was given a time delay to eliminate any correlation with delay line fibers. They were fed into the input of the device under the test (DUT). The attenuation levels of the device were set at 0 dB with a flat passband. Then, the output signals were transmitted to a coherent receiver to evaluate the bit error rate (BER) performance of the signals. The optical signal to noise ratio (OSNR) of the detected signals was swept by changing the noise power from amplified spontaneous emission (ASE) source of the EDFA using a variable optical attenuator. This routing condition emulated the worst transmission case, because the severe XT occurred on the same wavelength. The BER results are shown in Fig. 7(b). Our previous experiment revealed that the inter-lane XT significantly affects OSNR penalty [23]. However, in this experiment, no OSNR degradation was observed in the case without any external inputs and in the case with all lane inputs. These results indicate that the device had enough isolation between the sub-processor lanes. Next, we conducted a recirculating experiment. The experimental set up is shown in Fig. 8(a). In this experiment, we increased the number of recirculations from zero to seven, where zero means the back-to-back condition. The BER results are plotted as a function of recirculating number in Fig. 8(b); the BER degradation was very small. This suggests that the transmission properties were good on all sub-processor lanes. The BER results after a seven-span transmission are plotted in Fig. 8(c). The OSNR penalty was 0.05 dB at a BER of $10^{-3}$, indicating this device can work in actual networks. These good transmission characteristics are attributed to the low XT of the individual SBT structure and the sufficiently wide passband.

IV. APPLICATION TO DYNAMIC GAIN EQUALIZER

In SDM networks, SDM-compatible amplifiers must be able to compensate for the transmission loss of SDM fibers. MC-EDFAs that use a cladding pumping scheme are possible solutions because they allow for the sharing of the pump power, which could reduce the system’s cost, power consumption, and complexity [28]. However, the gain of such amplifiers typically exhibits significant core and wavelength dependency [29]. Therefore, a SDM-compatible gain equalizer has to compensate for gain non-uniformity by controlling optical power in each wavelength and spatial channels independently. Here, we decided to demonstrate the gain equalizing of an MC-EDFA as an applications of the device.

To examine the gain-flattening characteristics, a 12-core EDFA [30], which had a fan-out at the output port, was connected to the equalizer inputs. The amplified inputs were
flattened by tilting the input beam using the LCOS in the wavelength division. Then, the flattened spectra were equalized by varying the power supplied to the heater of the MZI-VOAs. Seven out of twelve cores were equalized in this experiment. Fig. 9(a) shows the ASE spectra from the gain equalizer before and after wavelength equalizing to $-5$ and $-10$ dB. The insets show the displayed phase pattern on the LCOS-SLM for wavelength equalizing. The wavelength-equalizing function was realized with the LCOS-SLM. Flattened ASE spectra over a 30-nm range in core 4 are shown in Fig. 9(b). The flattened spectra with ATT levels of 0, 5, 10, 15, and 20 dB and the full block using the MZI-VOAs are also plotted in Fig. 3(b). For comparison, the flattened spectra attenuated by using only the LCOS-SLM are shown in Fig. 9(c). The fluctuation of the spectra in Fig. 9(c) indicates ATT instability caused by the phase error of the LCOS-SLM ($\Delta \phi = \pm 5\%$). It is noticeable that the ATT levels of the spectra could be tuned by the MZI-VOAs while maintaining their flat spectral shape. On the other hand, the spectra attenuated by only the LCOS-SLM showed significant spectral non-uniformity. These results clearly mean that the combination of the LCOS-SLM and MZI-VOA is a powerful method for gain equalizing of spatial and wavelength channels.

On the basis of the above results, we examined the gain equalization of an MC-EDFA using the constructed device. The ASE spectra shown in Fig. 10(a) were flattened by the LCOS-SLM phase pattern. Although our device had a bandwidth of 1530-1570 nm, the target wavelength range was set to 1535–1565 nm because of the limited MC-EDFA bandwidth. The inter-core power differences shown in Fig. 10(b) were balanced by controlling the amount of electricity sent to each MZI-VOA’s heater. The equalized spectra are shown in Fig. 10(c). As can be seen, the ASE spectra were equalized over a 30-nm wavelength range with an accuracy of $\pm 0.8$ dB.

V. Conclusion

We demonstrated a multilane photonic spectral processor using a SPOC platform. The device includes an array of seven spectral processors. In addition, it can independently control the spatial and wavelength channels by utilizing a variable optical attenuator (VOA) integrated into the waveguide frontend. The device has low crosstalk between lanes; no degradation was observed in 100-Gbps DP-QPSK signal transmission. We demonstrated spatially multiplexed gain equalizers for MC-EDFAs using the constructed spectral processors. The device can control the spatial and wavelength channels independently by using MZI-VOAs and an LCOS-SLM. Gain flattening of seven-core MCF was achieved over a 30-nm wavelength range with an accuracy of $\pm 0.8$ dB. The scalability of our devices is determined by the pixel number of the LCOS and maximum diffraction angle from the waveguide frontend. By using state-of-the-art technology such as a 4K- or 8K-LCOS and a silicon-based optical phased array, we can support more large spatial channels such as 19- and 30-core fibers.
REFERENCES


Mitsumasa Nakajima (M’15) received the B.E. degree in applied physics from the Science University of Tokyo, Tokyo, Japan, in 2008, and the M.E. and Ph.D. degrees in material science from Tokyo Institute of Technology, Tokyo, in 2010 and 2015, respectively. He joined Nippon Telegraph and Telephone (NTT) Microsystem Integration Laboratories in 2010, where he was involved in the development of microelectromechanical system micromirrors for optical switch applications. He is currently with NTT Device Technology Laboratories, Atsugi, Japan. His research interests include ferroelectric materials and their applications, optical circuit design, and optical signal processing. He received the Young Engineer Award from the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan in 2013. He is a member of the IEICE.

Kenya Suzuki (M’00) received the B.E. and M.E. degrees in electrical engineering and the Dr.Eng. degree in electronics engineering from the University of Tokyo, Tokyo, Japan, in 1995, 1997, and 2000, respectively. He joined Nippon Telegraph and Telephone (NTT) in 2000. From September 2004 to September 2005, he was a Visiting Scientist at the Research Laboratory of Electronics, Massachusetts Institute of Technology. From 2008 to 2010, he was with NTT Electronics Corporation, Ibaraki, Japan, where he was involved in the development and commercialization of silica-based waveguide devices. Since 2014, he has been a Guest Chair Professor at the Tokyo Institute of Technology, Meguro, Japan. He is currently with NTT Device Technology Laboratories, Atsugi, Japan. His research interests include optical circuit design and optical signal processing. He received the Young Engineer Award from the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan in 2003. He is a member of the IEICE and the Physical Society of Japan.

Keita Yamaguchi received the B.S. and M.S. degrees in physics from Tsukuba University in 2009 and 2011, respectively. In 2011, he joined NTT Laboratorios, Kanagawa, Japan, where he conducted research on wavelength-selective switch systems. He has recently been researching liquid-crystal-on-silicon-based wavelength-selective switch and holographic phase modulation. He is a member of the Institute of Electronics, Information and Communication Engineers.
Hirotaka Ono (M’96–SM’15) received the B.S., M.S., and Ph.D. degrees in applied physics from Tohoku University, Sendai, Japan, in 1993, 1995, and 2004, respectively. He joined NTT Laboratories, Ibaraki, Japan, in 1995. He was also a Visiting Research Fellow with the Optoelectronics Research Centre, University of Southampton, U.K., from 2005 to 2006. He has been involved in research on optical fiber amplifiers, including L- and S-band erbium-doped fiber amplifiers. He has also undertaken research on highly nonlinear fiber devices, photonic crystal fibers, and wavelength-division-multiplexing transmission systems. He is now researching space-division-multiplexing (SDM) systems, including SDM optical amplifiers. He is a senior member of the Institute of Electronic, Information and Communication Engineers of Japan and the Optical Society of America and a member of the Japan Society of Applied Physics.

Takashi Goh (M’11) received the B.S. and M.S. degrees in electronics and communication engineering from Waseda University, Tokyo, Japan, in 1991 and 1993, respectively. In 1993, he joined NTT Opto-electronics Laboratories, Ibaraki, Japan, where he was involved in research on silica-based planar lightwave circuits such as thermo-optic switches and arrayed-waveguide grating multiplexers. From 2002 to 2004, he was involved in the development of optical communication systems including reconfigurable add-drop multiplexing systems in NTT Innovation Laboratories, Yokosuka, Japan. He is currently with NTT Device Technology Laboratories, Atsugi, Japan, where he has been involved in the research and development of optical device including advanced modulators and Nyquist filters for high-speed transmission and optical signal processing. He is a member of the Institute of Electronics, Information, and Communication Engineers of Japan and the Japan Society of Applied Physics.

Mitsunori Fukutoku received the B.S. and M.S. degrees from Tokushima University, Tokushima, Japan, in 1989 and 1991, respectively. He is the Group Leader of the Photonic Processing Systems Research Group, NTT Network Innovation Laboratories, Yokosuka, Japan, where he is responsible for research and development of optical nodes including ROADM systems for metro transport networks. He joined NTT Labs in 1991. He was responsible for research and development ROADM system. In 1999, he joined NTT Communications, where he planned to deploy long haul WDM systems. In 2006, he joined NTT West, where he developed Metro Ethernet System. Since 2009, he has been with NTT Network Innovation Labs.

Yutaka Miyamoto (M’93) was born in Tokyo, Japan, on December 8, 1963. He received the B.E. and M.E. degrees in electrical engineering from Waseda University, Tokyo, in 1986 and 1988, respectively, and the Dr.Eng. degree in electrical engineering from Tokyo University, Tokyo, Japan. In 1988, he joined NTT Transmission Systems Laboratories, Yokosuka, Japan, where he was involved in research and development on high-speed optical communications systems including the first 10-Gbit/s terrestrial optical transmission system (FA-10G) using erbium-doped fiber amplifier inline repeaters. He then joined NTT Electronics Technology Corporation between 1995 and 1997, where he was involved in the planning and product development of high-speed optical modules operating 10 Gbit/s and higher. Since 1997, he has been with NTT Network Innovation Labs, Yokosuka, where he has been involved in research and development of optical transport technologies offering the channel rates from 40 Gbit/s to 1 Tbit/s. He is currently a Senior Distinguished Researcher and Director of the Innovative Photonic Network Research Center, NTT Network Innovation Laboratories. His current research interests include scalable high-capacity optical transport systems with advanced modulation formats, digital signal processing, optical preprocessing, and space-division multiplexing. He is a fellow of the Institute of Electronics, Information, and Communication Engineers of Japan.

Toshikazu Hashimoto received the B.S. and M.S. degrees in physics from Hokkaido University, Hokkaido, Japan, in 1991 and 1993, respectively. Since 1993, he has been with NTT Laboratories, where he is researching hybrid integration of semiconductor lasers and photodiodes on silica-based planar lightwave circuits and the wavefront matching method. He is a member of the Institute of Electronics, Information and Communication Engineers of Japan, the Physical Society of Japan, and the Optical Society.