High-output Optical Transmitter and High-sensitivity Optical Receiver for 400-Gbit/s 40-km Fiber-amplifier-less Transmission

Shigeru Kanazawa, Takahiko Shindo, Yasuhiko Nakanishi, Masahiro Nada, Koichi Hadama, Mingchen Chen, Shoko Tatsumi, Atsushi Kanda, and Hirotaka Nakamura

Abstract

We developed a high-output optical transmitter and a high-sensitivity optical receiver for long-distance transmission in the All-Photonics Network that is being promoted under IOWN (the Innovative Optical and Wireless Network). This article introduces the 400-Gbit/s optical transmitter with a semiconductor optical amplifier-assisted extended-reach electro-absorption modulator integrated distributed feedback laser called AXEL, a key device for higher optical output, and the 400-Gbit/s optical receiver with an avalanche photodiode, a key device for higher sensitivity.

Keywords: intensity-modulation direct-detection (IM-DD), AXEL, APD

1. Introduction

The amount of data handled by communication networks has been increasing dramatically with the development of cloud services and other new services, and traffic volume has also been increasing sharply. In response, NTT proposed the Innovative Optical and Wireless Network (IOWN) to increase transmission capacity, decrease latency, reduce power consumption, and provide excellent flexibility in the communication network.

The All-Photonics Network (APN), one of the three main components of IOWN, will introduce photonics technology everywhere, from the network to the terminal and from short distances to long distances, to achieve overwhelmingly lower power consumption, higher quality, greater capacity, and lower latency in network-data transmission.

At the NTT Device Innovation Center, we developed an optical transmitter and optical receiver for intensity modulation format to fabricate a compact and low-power-consumption transceiver and increase transmission capacity. To fabricate the transmitter and receiver for long-distance transmission, a higher output optical transmitter and higher sensitivity optical receiver are needed. We therefore conducted research and development on a semiconductor optical amplifier (SOA)-assisted, extended-reach electro-absorption modulator integrated distributed feedback (EADFB) laser called AXEL [1], which is a key device for high optical output, and an avalanche photodiode (APD) [2], which is a key device for high sensitivity. This work resulted in the development of an optical transmitter and receiver that are capable of transmitting a 400-Gbit/s signal over a distance of 40 km [3, 4]. The developed transmitter and receiver

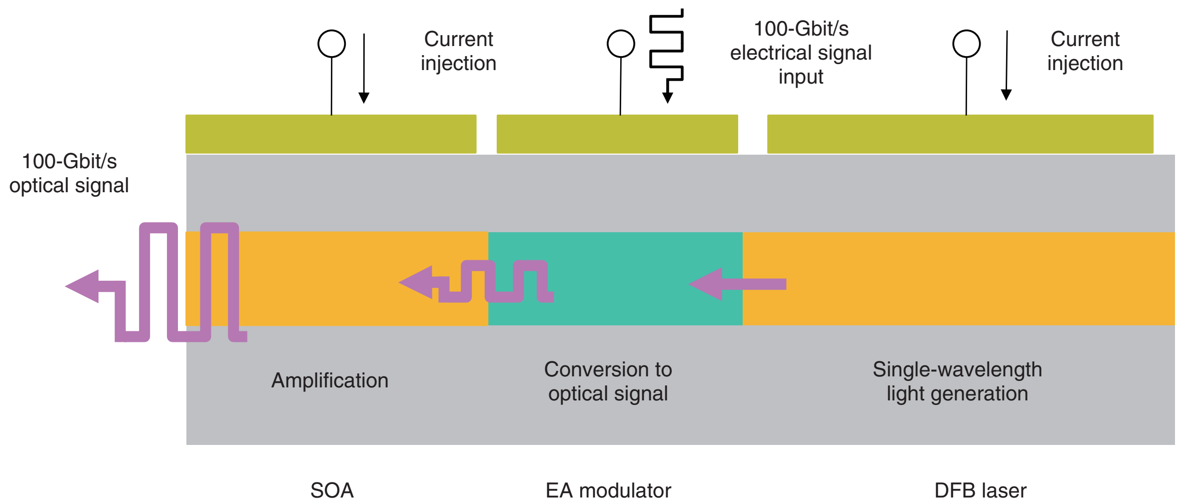


Fig. 1. Schematic of AXEL chip.

extend the region in which intensity modulation can be applied, contributing to reducing network-interface device size and power consumption.

2. AXEL

The key device of the high-output optical transmitter is a high-speed, high-output optical transmission device, which is generally an EADFB laser that generates an optical signal of 100 Gbit/s per chip. This laser comprises a DFB laser that emits single-wavelength light and an EA modulator that converts an electrical signal to a high-speed, high-quality optical signal. However, conventional EADFB lasers have high optical loss in the EA modulator and inhibit the increase in higher output power.

To address this issue, we have been developing AXEL as a key transmitter that can achieve high-speed optical transmission with high output (**Fig. 1**). An SOA is driven by current injection, and light incident to the SOA is amplified as it propagates. In conventional EADFB lasers, the intensity of the light output by the DFB laser is decreased by modulation in the EA modulator, but in AXEL, the light is amplified by the SOA to obtain a high-output optical signal. The SOA is fabricated from the same semiconductor materials as the DFB laser; therefore small, integrated AXEL chips can be fabricated with the same process, enabling low-cost mass production. Because each SOA chip must amplify a high-speed 100-Gbit/s optical signal, this SOA uses a new optical amplification layer that efficiently converts electrical current into light with less degradation in the optical waveform, thus achieving output of a 100-Gbit/s signal with no loss of quality. The AXEL chip we developed is thus capable of outputting a 100-Gbit/s optical signal with an intensity of +8.0 dBm or more [1]. An optical transmitter that generates a 400-Gbit/s optical signal can be achieved with an array of four discrete AXEL chips.

3. APD

The key device of the high-sensitivity photoreceiver is a high-speed, high-sensitivity PD. The PDs that are generally used in receivers have a theoretical opto-electrical conversion efficiency of 100%, but, in most cases, the actual efficiency is only a few tens of percent because of loss at light incidence and incomplete absorbance of light within the PD.

We developed an APD, a special PD designed to serve as a high-speed, high-sensitivity receiver. A strong electric field is induced within the APD, and more electrons and holes are generated by collisions of ionized photoelectrons in the field. The result is an opto-electrical conversion efficiency that can exceed 100%, enabling the fabrication of a high-sensitivity optical receiver. The main components of the APD are light-absorption layers and an avalanche amplification layer (**Fig. 2**). The optical signal is converted to an electrical signal in the absorption layers, and the resulting electrical signal is amplified in the amplification layer.

The APD converts a 100-Gbit/s optical signal to an

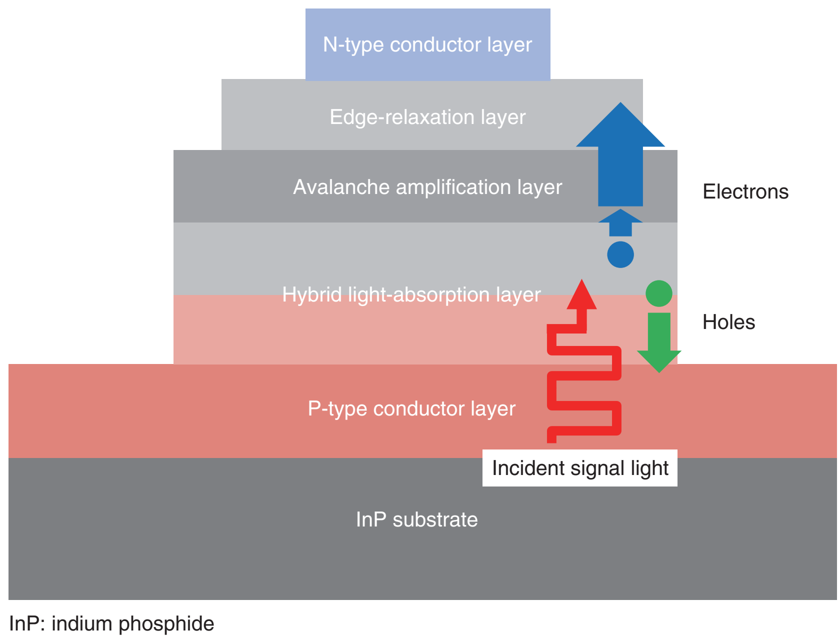


Fig. 2. Schematic of APD chip.

electrical signal. PDs generally must sacrifice sensitivity to received light to achieve higher speed. They also require a waveguide that makes photonic coupling of the incident optical signal to them difficult. For this APD, we adopted a hybrid two-layer light-absorption structure that combines one absorption layer that uses electron diffusion as the main carrier-transport mechanism and another absorption layer that uses hole drift as the main carrier-diffusion mechanism. This makes it possible for the optical receiver to handle a 100-Gbit/s signal while maintaining high sensitivity and facilitating optical coupling with a vertical injection structure [2]. An optical receiver that converts a 400-Gbit/s optical signal to an electrical signal can be fabricated by mounting four APD chips.

4. 400-Gbit/s high-output optical transmitter

Our four-channel, 400-Gbit/s optical transmitter achieves high output power with four AXEL chips that are mounted inside the transmitter on four subassemblies (**Fig. 3(a)**) [3]. Each chip outputs a 100-Gbit/s optical signal. The light wavelengths output from the subassemblies, 1295.5 nm (Lane 0), 1300 nm (Lane 1), 1304.5 nm (Lane 2), and 1309.1 nm (Lane 3), are determined using a local area network-wavelength division multiplexing grid. The output light is collimated after passing through the first lens and input to an optical multiplexer that comprises a mirror, glass block, and wavelength filters. The 400-Gbit/s optical signal from the multiplexer is passed through an isolator and the second lens and then coupled to an internal optical waveguide in a Lucent connector (LC) receptacle. A photograph of the fabricated compact 4-channel optical transmitter is shown in **Fig. 3(b)**. The device is 18.2 mm long, 6.2 mm wide, and 5.4 mm high, small enough to be mounted in a quad small-form-factor pluggable, double density (QSFP-DD) optical transceiver.

We measured the waveform eye diagrams and the output power for operation at 400 Gbit/s. The AXEL chip temperature was 50°C. The laser diode and SOA currents were 80 and 40 mA, respectively. The measured electrical signal was 53.125 Gbaud, and the amplitude voltage of the four-level pulse amplitude modulation signal was 0.75 Vpp. The eye diagrams were observed with a sampling oscilloscope after the signal was passed through a 26.6-GHz low-pass filter and equalization with a transmitter dispersion eye closure quaternary (TDECQ) filter. Clear eye openings were obtained for all lanes, with TDECQ (an indicator of waveform quality) of 2.4 dB or less (**Fig. 4**). Optical output power (optical modulation amplitude (OMA)) of at least +4.7 dBm was also confirmed for all lanes, indicating the high output

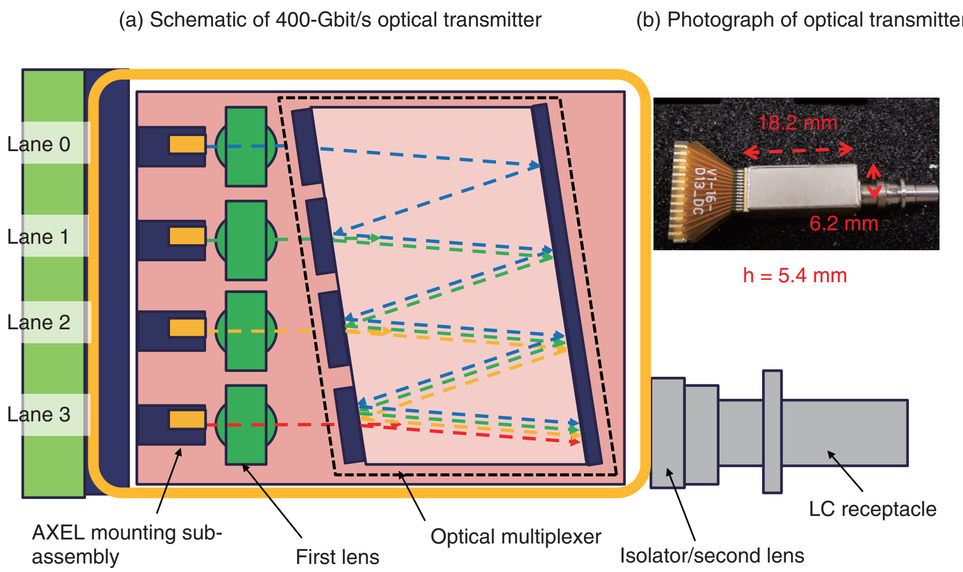


Fig. 3. 400-Gbit/s optical transmitter.

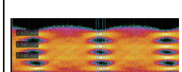
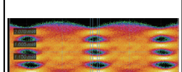
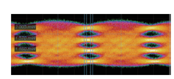
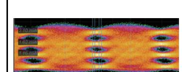
	Lane 0	Lane 1	Lane 2	Lane 3
Eye diagram				
TDECQ (dB)	1.8	2.4	1.2	1.8
Extinction ratio (dB)	3.9	4.2	3.8	4.3
OMA (dBm)	4.7	5.8	5.8	6.3

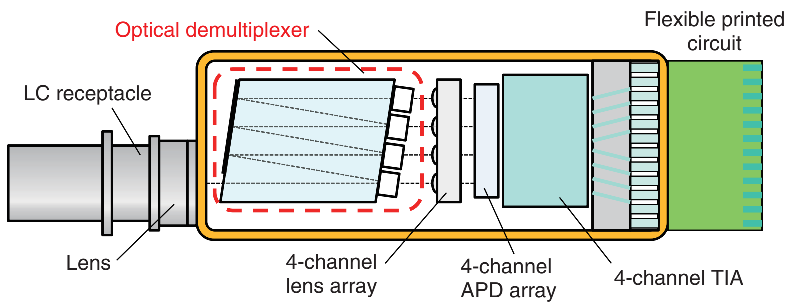
Fig. 4. Eye diagrams for operation at 400 Gbit/s.

characteristic of the AXEL chip.

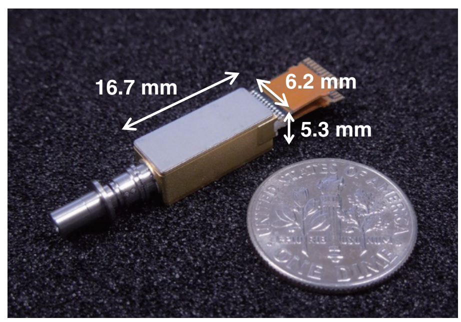
5. 400-Gbit/s high-sensitivity optical receiver

The optical receiver comprises a collimating lens for the light output from the LC receptacle, optical demultiplexer for demultiplexing the four-wavelength optical signal from the transmitter, four-channel lens array, four-channel APD array, and four-channel trans-impedance amplifier (TIA). The optical signal input to the receiver is separated into wavelengths of 1295.5, 1300, 1304.5, and 1309.1 nm by the optical demultiplexer (**Fig. 5(a)**) [4]. The demultiplexed optical signals pass through the lens array and input to the four-channel APD array for conversion to amplified electrical signals. The four 100-Gbit/s electrical signals are output from the receiver via the TIA. A photograph of the fabricated four-channel optical receiver is shown in **Fig. 5(b)**. The device is 16.7 mm long, 6.2 mm wide, and 5.3 mm high, small enough to be mounted in a QSFP-DD optical transceiver in the same manner as the transmitter described above.

We measured the bit-error-rate (BER) of the fabricated four-channel optical receiver with the system configuration illustrated in **Fig. 6**. The four-channel optical transmitter outputs one 100-Gbit/s signal per channel to generate a total signal-transmission rate of 400 Gbit/s. The extinction ratio for the optical signal ranges from 3.8 to 4.3 dB. The signal is input to the four-channel receiver via the variable attenuator, converted to an electrical signal, then output. The output



(a) Schematic of 400-Gbit/s optical receiver



(b) Photograph of optical receiver

Fig. 5. 400-Gbit/s optical receiver.

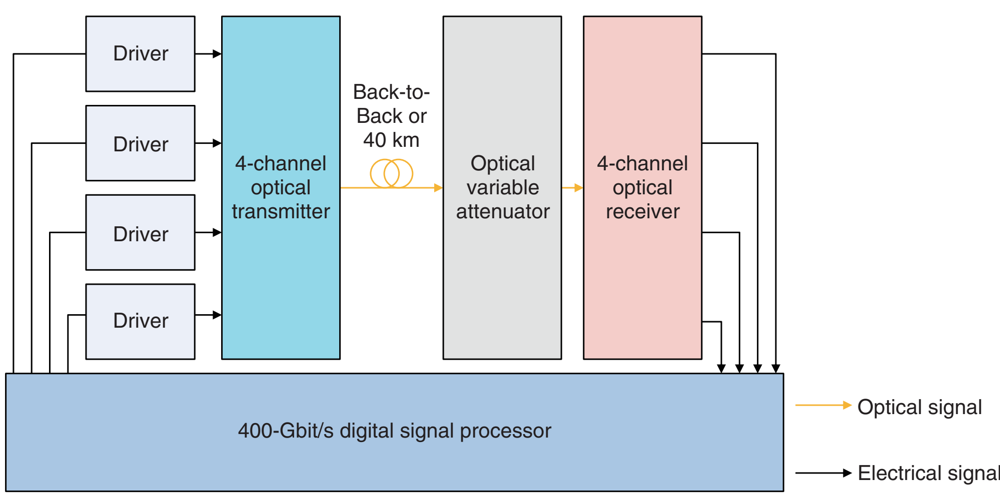


Fig. 6. Evaluation system configuration.

signal is demodulated by the 400-Gbit/s digital signal processor and the BER is calculated under discrete operation.

The BER for each channel is shown in **Fig. 7**. In a back-to-back (BtoB) configuration, where the optical transmitter and optical receiver are connected almost directly, the minimum receiving sensitivity for a BER of 2.4×10^{-4} ranged from –13.5 to –14.0 dBm for

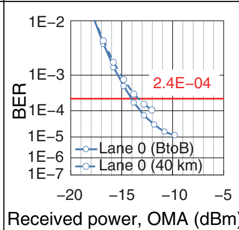
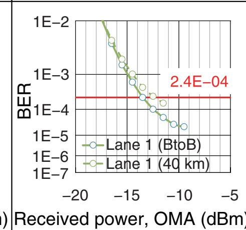
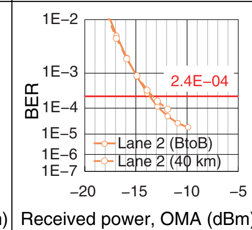
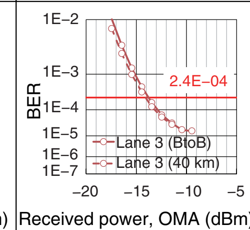
		Lane 0	Lane 1	Lane 2	Lane 3
BER					
Receiver sensitivity (dBm)	BtoB	−14.0	−13.5	−13.7	−13.8
	40 km	−13.4	−12.3	−13.4	−14.1

Fig. 7. BERs for operation at 400 Gbit/s.

OMA. When the receiver was connected to a 40-km standard single-mode fiber as a transmission line, the minimum receiving sensitivity for OMA ranged from –12.3 to –14.1 dBm. These results indicate that the transmission distance in a 400-Gbit/s transmission service can be extended to 40 km by combining a four-channel optical transmitter assembled with AXEL chips and a four-channel optical receiver assembled with APD chips and using intensity modulation.

6. Conclusion

We fabricated a compact high-output four-channel AXEL transmitter and compact high-sensitivity four-channel APD receiver for 400-Gbit/s application. The transmitter and receiver are capable of transmitting a 400-Gbit/s optical signal to a distance of 40 km over optical fiber by intensity modulation, with the expectation of a reduction in power consumption. These indicate that the fabricated AXEL transmitter and APD receiver are promising technology for high-capacity and energy-efficient networks.

References

[1] T. Shindo, N. Fujiwara, S. Kanazawa, M. Nada, Y. Nakanishi, T. Yoshimatsu, A. Kanda, M. Chen, Y. Ohiso, K. Sano, and H. Matsuzaki, “High Power and High Speed SOA Assisted Extended Reach EADFB Laser (AXEL) for 53-Gbaud PAM4 Fiber-amplifier-less 60-km Optical Link,” J. Lightw. Technol., Vol. 38, No. 11, pp. 2984–2991, 2020.

[2] M. Nada, T. Yoshimatsu, F. Nakajima, K. Sano, and H. Matsuzaki, “A 42-GHz Bandwidth Avalanche Photodiodes Based on III-V Compounds for 106-Gbit/s PAM4 Applications,” J. Lightw. Technol., Vol. 37, No. 2, pp. 260–265, 2019.

[3] S. Kanazawa, T. Shindo, M. Chen, N. Fujiwara, M. Nada, T. Yoshimatsu, A. Kanda, Y. Nakanishi, F. Nakajima, K. Sano, Y. Ishikawa, K. Mizuno, and H. Matsuzaki, “High Output Power SOA Assisted Extended Reach EADFB Laser (AXEL) TOSA for 400-Gbit/s 40-km Fiber-amplifier-less Transmission,” J. Lightw. Technol., Vol. 39, No. 4, pp. 1089–1095, 2021.

[4] A. Kanda, T. Yoshimatsu, M. Nada, S. Kanazawa, Y. Nakanishi, F. Nakajima, H. Matsuzaki, and K. Sano, “400-Gbit/s High-sensitivity APD-ROSA for 4λ LAN-WDM 40-km Optical Link,” Proc. of the 25th Opto-Electronics and Communications Conference (OECC 2020), T4-5.4, Taipei, Taiwan, Oct. 2020.

Shigeru Kanazawa

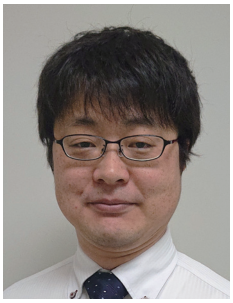
Senior Research Engineer, Metro-Access Network Device Project, NTT Device Innovation Center.

He received a B.E., M.E., and Ph.D. in electronic engineering from the Tokyo Institute of Technology in 2005, 2007, and 2016. He joined NTT Photonics Laboratories (now NTT Device Innovation Center) in 2007. He is engaged in the research and development of optical semiconductor devices and integrated devices for optical communications systems. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE)/Photonics Society and a member of the Japan Society of Applied Physics (JSAP) and the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Takahiko Shindo

Senior Research Engineer, Metro-Access Network Device Project, NTT Device Innovation Center.

He received a B.E., M.E., and Ph.D. in electrical and electronic engineering from the Tokyo Institute of Technology in 2008, 2010, and 2012. He received a research fellowship for young scientists from the Japan Society for the Promotion of Science from 2010 to 2012. After obtaining his Ph.D., he worked as a research fellow at the Japan Society for the Promotion of Science. In April 2013, he joined NTT Photonics Laboratories (now NTT Device Innovation Center), where he is currently engaged in research on optical semiconductor devices. He is a member of the IEEE Photonics Society, JSAP, and IEICE.



Yasuhiko Nakanishi

Senior Research Engineer, Metro-Access Network Device Project, NTT Device Innovation Center.

He received a B.E. and M.E. from Hokkaido University in 2000 and 2002. He joined NTT Access Network Service Systems Laboratories in 2002, where he has been involved in the research and development of optical communication systems and devices. He is a member of IEICE.

Masahiro Nada

Senior Research Engineer, Metro-Access Network Device Project, NTT Device Innovation Center.

He received an M.E. in applied physics from the University of Electro-Communications, Tokyo, in 2009 and Ph.D. in engineering from the University of Tokyo in 2017. He joined NTT Photonics Laboratories in 2009 and has worked on high-speed, high-responsivity APDs and their application to optical-fiber communications systems. He is currently with the NTT Device Innovation Center. He was the recipient of the Young Researcher's Award from IEICE in 2014 and the Electronics Society Award from IEICE Electronics Society in 2021. He is a senior member of IEICE and IEEE. He is also a member of Optica.

Koichi Hadama

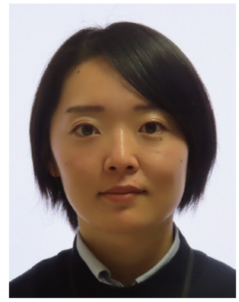
Senior Research Engineer, Metro-Access Network Device Project, NTT Device Innovation Center.

He received a B.E. and M.S. in applied physics and advanced materials science from the University of Tokyo in 1999 and 2001. He joined NTT Telecommunication Energy Laboratories in 2001. Since then, he has worked on research and development of free-space optical modules for WDM network systems. He is currently with the NTT Device Innovation Center, where he is engaged in the development of optical and electrical modules for metro and access networks. He is a member of IEICE.

Mingchen Chen

Research Engineer, Metro-Access Network Device Project, NTT Device Innovation Center.

He received a B.E. and M.E. in electronic engineering from the University of Electro-Communications, Tokyo, in 2010 and 2012 and Ph.D. in engineering from the University of Electro-Communications in 2015. He joined the NTT Device Innovation Center in 2015 and worked on the development of high-speed wavelength swept source for the optical coherence tomography applications. He is currently engaged in the development of a semiconductor laser device for optical communication applications. He is a member of IEICE.



Shoko Tatsumi

Engineer, Metro-Access Network Device Project, NTT Device Innovation Center.

She received a B.E. and M.E. in engineering from Osaka University in 2011 and 2013. She joined NTT Photonics Laboratories (now NTT Device Innovation Center) in 2013 and worked on optics related to optical coherence tomography and microscopy. She is currently engaged in the development of high-speed, high-responsivity APDs and their application to the optical communication applications.

Atsushi Kanda

Engineer, Metro-Access Network Device Project, NTT Device Innovation Center.

He received a B.E. from Waseda University, Tokyo, M.E. from the Tokyo Institute of Technology, and Ph.D. from University of Tsukuba, Ibaraki, in 1988, 1990, and 2017. In 1990, he joined NTT Radio Communication Systems Laboratories, where he was engaged in research on microwave and millimeter-wave integrated circuits for wireless communication. He moved to NTT Photonics Laboratories in 1999 and is now at the NTT Device Innovation Center, where he is involved in the research and development of electronic and optical devices for optical networks. He is a member of IEEE.

Hirotaka Nakamura

Senior Research Engineer, Supervisor, Metro-Access Network Device Project, NTT Device Innovation Center.

He received a B.E. in applied physics from the University of Tokyo in 1999 and Ph.D. from Hokkaido University in 2011. In 1999, he joined NTT Access Network Service Systems Laboratories, where he was engaged in research on optical technologies of high-speed passive optical networks. Since 2020, he has been with the NTT Device Innovation Center, where he is engaged in the research and development of laser diodes, photodiodes, and analog integrated circuits for optical metro and access networks. He is a member of IEICE. He has been participating in ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) and FSAN (Full Service Access Network) since 2009.