Net-1.8 Tbps/λ Transmission Enabled by C+L-band InP-based Coherent Driver Modulator

Josuke Ozaki[1], Yoshihiro Ogiso[1], Hiroshi Yamazaki[2], Masanori Nakamura[2], Kenta Sugiura[1], Kazuya Nagashima[3], Yasuaki Hashizume[4], Nobuhiro Nunoya[1], Yutaka Miyamoto[2], Mitsuteru Ishikawa[1]

[1] NTT Innovative Devices Corporation, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa, Japan
[2] NTT Network Innovation Laboratories, NTT Corporation, 1-1, Hikari-no-oka, Yokosuka-shi, Kanagawa, Japan
[3] Furukawa Electric Co., Ltd., 6, Yawatakaigandori, Ichihara-shi, Chiba 290-8555, Japan
[4] NTT Device Innovation Center, NTT Corporation, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa, Japan
josuke.ozaki@ntt-devices.com

Abstract: Using a newly developed InP-based C+L-band supported coherent driver modulator with an electro-optic 3-dB bandwidth above 90 GHz, an 80km transmission with a net bit rate of 1.8Tbps/λ in the C+L band was successfully demonstrated. © 2024 The Author(s)

1. Introduction

To accommodate the rapidly increasing data traffic, optical transmitters and receivers must be miniaturized and operated at high baud rates and with high-order multi-level modulation formats so that digital coherent optical communication systems can achieve small footprints and high data rates per wavelength. A high-bandwidth coherent driver modulator (HB-CDM) [1], in which a driver die and a modulator chip are co-packaged to reduce RF losses and the footprint, is known as a modulator for metro and long-haul coherent networks. Since the CDM is intended for high-end applications, the modulator chip used in the CDM are required to have high bandwidth and low driving voltage characteristics, such as those made of InP [2, 3] and thin-film $LiNbO_3$ [4, 5].

As the baud rate increases, the bandwidth of the modulation signal required per channel becomes wider and the number of channels that can be transmitted in the C-band decreases, thus increasing the need for wavelength extension, such as extending the wavelength bandwidth from the conventional C-band to the super C-band [6] and L-band. InP modulators are known for their excellent optical and RF characteristics, but because they utilize electroabsorption and electrorefraction effects, such as the quantum-confined Stark effect (QCSE) and the Franz-Keldysh effect, they have a large wavelength dependence, and it is generally hard to extend the wavelength range. In fact, the CDMs with InP modulators currently available on the market for the C band and L band are sold separately, which means that the modulator chip's epitaxial and waveguide design differs depending on the band used.

In this paper, we report a newly developed C+L-band supported CDM with an InP modulator chip which has a wide range of wavelengths by optimizing the epitaxial and waveguide structure. As for the CDM's characteristics over the C+L band, the electro-optic (EO) 3-dB bandwidth is more than 90 GHz, the insertion loss (IL) at maximum transmission, including a bias loss of $V_\pi = 2$ V, is less than 8 dB, and the extinction ratio (ER) is 28 dB or more. In addition, we performed and experiment of up to 1.8 Tbps/λ in a back-to-back and 80 km transmission over the C+L band, which is achieved by using 180 Gbaud probabilistically constellation-shaped 144-level quadrature amplitude modulation (PCS-144QAM) signals. This is the first report of C+L-band operation of an InP-based CDM, and the 1.8 Tbps/λ 80 km transmission is the highest capacity reported for a CDM.

2. Design and characteristic of coherent driver modulator

Figure 1(a) shows a photograph of the developed CDM. The package body size is 11.9 × 29.8 × 4.35 mm^3. We were able to reduce the package height by about 1 mm compared with our previous CDM package [3] by reducing the thickness of a chip carrier and using a low loop wire. The CDM has the following three key components: a package

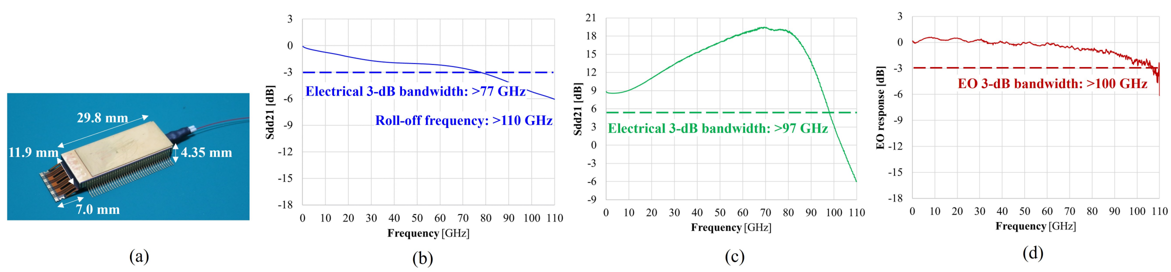

Fig. 1. (a) Photograph of CDM. (b) Sdd21 of FPC package. (c) Sdd21 of driver die. (d) Small-signal EO response of modulator chip.

with a flexible printed circuit (FPC) as the RF interface and a lead pin as the DC interface, a 4-channel SiGe BiCMOS driver die, and an InP-based n-i-p-n heterostructure twin IQ modulator chip with a differential capacitively loaded traveling-wave electrode.

Figure 1(b), (c), and (d) respectively show the small-signal RF characteristics of the package with the 8.5-mm-long FPC in a flat condition, the driver die with wire inductance connected to the input and output driver pad, and the modulator chip. Regarding the FPC package, the roll-off frequency exceeding 110 GHz was confirmed. In our previous FPC package, roll-off occurred around 100 GHz due to the spread of the electromagnetic field in the solder connection pad area between the FPC and the ceramic package. We suppressed this leakage by reinforcing the ground in the ceramic by using the small-diameter vias to shift the roll-off frequency to the higher frequency side [4]. In addition, simulations showed that the roll-off frequency exceeds 130 GHz, which is beyond the measurement limit of the equipment used in this study. The driver has a differential output amplitude of 2.5 V_{ppd} at 60 Ω (differential), and a measured electrical (EE) 3-dB bandwidth of approximately 98 GHz with more than 10 dB peaking at 70 to 80 GHz in our assembly. We revised the modulator's structure, including its epitaxial layer and waveguide structure, to increase the electric field strength applied to the multiple quantum well (MQW) and improve the modulation efficiency, resulting in an InP modulator chip capable of operating over the C+L band with low optical propagation loss and low bias absorption loss. The InP modulator has an EO 3-dB bandwidth of over 100 GHz with a half-wave voltage (V_π) of 2 V over the C+L band, which is the highest EO bandwidth among the InP modulator chips reported to date. In addition, the package and modulator do not have a significant roll-off before 110 GHz, which indicates that they have the potential to support 200-Gbaud class operations.

Figure 2(a), (b), (c) and (d) shows the measured optical characteristics and small-signal EO response of the CDM. As shown in Fig. 2(a), the insertion loss after X and Y polarization combining and per polarization, including the absorption loss at V_π of 2 V at maximum transmissions, is below 8 dB and 11 dB, respectively, from the wavelength of 1527 nm to 1610 nm. These values are more than 5 dB less than the IL specified in the OIF [1] and cover the C+L band. In addition, although this InP modulator chip is not equipped with a semiconductor optical amplifier or a variable optical attenuator (VOA), the polarization-dependent loss is small, less than 0.5 dB. The IL tends to increase a little after 1580 nm, which we consider to be caused by the multi-mode interferometer waveguide crossing and it is possible to reduce the wavelength dependence by optimizing the crossing design. This is because the bias loss for a V_π of 2 V is not degraded at longer wavelengths and is suppressed to less than 1 dB in the entire C+L band, as shown in Fig. 2(c). The ER of the child Mach-Zehnder interferometer is shown in Fig. 2(c) and is more than 28 dB at wavelengths from 1527 nm to 1610 nm, which is sufficient for high-order modulation formats such as 64 QAM or more. Figure 2(d) shows the measured small-signal EO response normalized at 1 GHz. The EO 3-dB bandwidth is greater than 90 GHz. In general, since the transmitter can operate at baud rates up to about twice the 3-dB EO bandwidth, the CDM is capable of 180-Gbaud class operation.

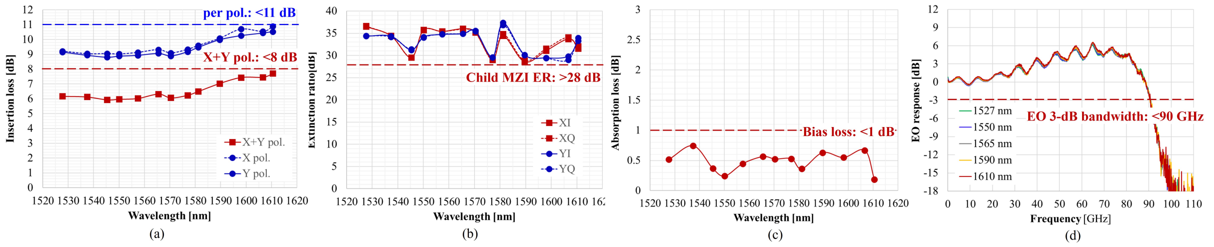

Fig. 2. CDM's optical and RF characteristics (a) Insertion loss. (b) Extinction ratio of child MZI. (c) Bias loss for V_π of 2 V. (d) Small-signal EO response.

3. Digital coherent transmission result over C+L band

Figure 3 shows the setup for 180-Gbaud digital coherent transmission. We used an offline PC and 256 GSa/s arbitrary waveform generator (AWG) with a 3-dB analog bandwidth of >80 GHz to emulate a digital signal processor (DSP) and digital-to-analog converter (DAC). An external-cavity laser (ECL) with a linewidth <100 kHz was used as a continuous wave (CW) input light source to the CDM, which was soldered to a printed circuit board (PCB) for the device control and evaluation. The output light from the CDM was amplified by an erbium-doped fiber amplifier (EDFA), passed through the VOA, adjusted to the optimum optical power, and transmitted over the 80-km standard single-mode fiber (SSMF), an EDFA, a VOA, and an optical band-pass filter (OBPF). An optical crossbar switch was used to switch between the back-to-back and 80-km transmission paths. The optical signal was received by a coherent receiver frontend with a 3-dB analog bandwidth of >100 GHz followed by a 256-GS/s 110-

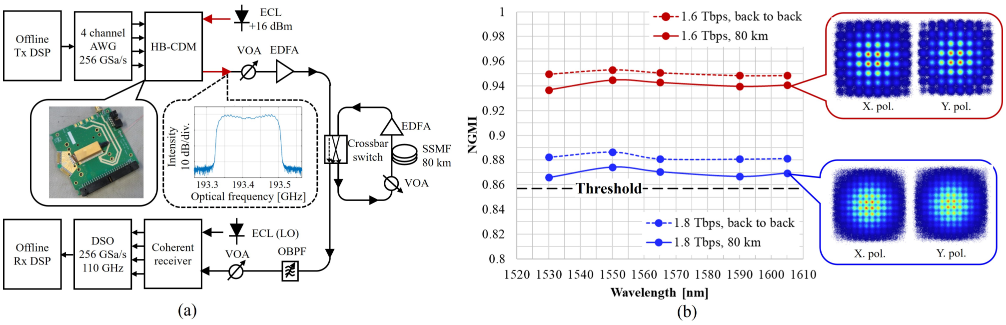

Fig. 3. (a) Experimental setup. (b) NGMI of back-to-back and 80-km SSMF transmission of 1.8 Tbps (DP 180-Gbaud PCS-144QAM with entropy of 12.86 bits/symbol) and 1.6 Tbps (DP 180-Gbaud PCS-64QAM with entropy of 11.05 bits/symbol).

GHz digital storage oscilloscope (DSO). The dual polarization (DP) 180-Gbaud PCS-144QAM RF signals with an entropy of 12.86 bits/symbol and 64-QAM RF signals with an entropy of 11.05 bits/symbol were input to the CDM. Assuming the use of forward error-correction (FEC) codes with a total code rate of 0.826 [8], the net data rates of the two formats are {12.86−(1−0.826)*16)/1.0079*0.18}=1.80 Tbps and {11.05−(1−0.826)*12)/1.0079*0.180}=1.60 Tbps, respectively. The RF signals were pulsed-shaped using a root-raised-cosine (RRC) filter, and a roll-off factor of 0.05. The length was approximately 3×10^5 symbols, and the pilot overhead (OH) was set to 0.79%. The optical spectrum at 1550 nm with the 180-Gbaud PCS-144QAM signal is shown in Fig. 3(a). On the transmitter side, a fixed linear digital equalizer was used to partially compensate for the frequency channel response without optical pre-equalization. The receiver side used basically the same offline DSP as in [7], which includes a frequency-domain 8×2 adaptive equalizer with an FFT block size of 4,096. The performance metric was the normalized generalized mutual information (NGMI).

The measured NGMIs of the 1.8 Tbps and 1.6 Tbps transmissions are plotted against the wavelength in Fig. 3(b). The dotted and solid lines, respectively, show the NGMIs of back-to-back and after 80-km SSMF over the C+L band. The NGMIs exceeded the threshold of 0.857 [8], indicating successful 80-km transmissions at data rates up to 1.8 Tbps over the C+L band. The results of 80 km transmissions for 1.6 Tbps showed a sufficient margin over the threshold, suggesting the possibility of transmitting much longer distances. The significant performance improvements over those of our previous CDM [9] can be attributed to the optimization of the driver's peaking and the increase in the CDM bandwidth.

4. Conclusion

180-Gbaud digital coherent transmissions were achieved using a C+L-band InP-based CDM. We successfully transmitted the DP 180-Gbaud PCS-144QAM signal with an entropy of 12.86 bits/symbol (net bit rate of 1.8 Tbps) over 80-km SSMF in the C+L band. This is the highest baud rate and transmission capacity per wavelength ever reported for a CDM.

Acknowledgements: This work is partially supported by the R&D program (#04501) commissioned by the National Institute of Information and Communications Technology (NICT).

4. Reference

[1] "Implementation agreement for the high bandwidth coherent driver modulator (HB-CDM)," OIF Implementation Agreement No. OIF-HB-CDM02.0, 2021. [Online]. Available: https://www.oiforum.com/wp-content/uploads/OIF-HB-CDM-02.0.pdf.
[2] Y. Ogiso et al., "80-GHz bandwidth and 1.5-V Vπ InP-based IQ modulator," J. Lightw. Technol., vol. 38, no. 2, pp. 249–255, Jan. 2020.
[3] J. Ozaki et al., "Over-85-GHz-Bandwidth InP-Based Coherent Driver Modulator Capable of 1-Tb/s/λ-Class Operation," J. Lightw. Technol., vol. 41, no. 11, pp. 3290-3296, Jun., 2023.
[4] M. Xu et al., "Advances in Ultra-Wideband LiNbO3 Thin-Film Modulators," in Proc. Opt. Fiber Commun. Conf. Exhib., Tu3C.1, 2023.
[5] S. Makino et al., "Demonstration of thin-film lithium niobate high-bandwidth coherent driver modulator," in Proc. Opt. Fiber Commun. Conf. Exhib., M1D.2, 2022.
[6] F. Pittalà et al., "72.64 Tb/s DWDM Transmission over 100 km G.654D Fiber Using Super C-Band Erbium-Doped Fiber Amplification," in Proc. Opt. Fiber Commun. Conf. Exhib., W3C.4, 2022.
[7] M. Nakamura et al., "High Information Rate of 128-GBaud 1.8-Tb/s and 64-GBaud 1.03-Tb/s Signal Generation and Detection Using Frequency-Domain 8×2 MIMO Equalization," in Proc. Opt. Fiber Commun. Conf. Exhib., M3H.1, 2022.
[8] M. Nakamura et al., "Spectrally Efficient 800 Gbps/Carrier WDM Transmission with 100-GHz Spacing Using Probabilistically Shaped PDM-256QAM," in Proc. IEEE Eur. Conf. Opt. Commun., We3G.5, 2018.
[9] Di Che et al., "An Integrated Coherent Driver Modulator Enabled 1.6-Tb/s Coherent Transmission," in Proc. IEEE Eur. Conf. Opt. Commun., W3C.4, 2023.