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Transmission of 160.7-GBaud 1.64-Tbps Signal Using Phase-Interleaving Optical Modulator and Digital Spectral Weaver

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Abstract *We demonstrate a bandwidth-extending transmitter employing an 8×4 digital spectral weaver, CMOS DACs, and an InP integrated phase-interleaving optical modulator. The transmitter generates single-carrier 160.7-GBaud signals achieving net data rates of 1.68 Tbps back-to-back and 1.64 Tbps after 80-km SSMF transmission. ©2022 The Author(s)*

Introduction

Digital coherent optical transmission technology is evolving toward higher per-wavelength data rates to accommodate ever-increasing data traffic more efficiently. Fig. 1 summarizes recently reported experimental results at per-wavelength net data rates of 1 Tbps or higher achieved with single continuous-wave (CW) transmission laser. Such high data rates have been achieved by using CMOS [1-3], InP [4], or SiGe [5-12] digital-to-analog converters (DACs) in the transmitters with a conventional configuration, where a single DAC is used for each signaling dimension. SiGe DACs have enabled very high data rates of up to 1.96 Tbps [11] at symbol rates of around 130 GBaud. Meanwhile, in pursuit of higher symbol rates, bandwidth-extending transmitters using multiple DACs for each dimension have also been demonstrated [13-17]. They employ additional digital preprocessors and analog electronics to synthesize arbitrary signals having extended analog bandwidths. Such technologies are also promising for increasing data rates utilizing CMOS DACs, which are best suited for practical applications but by themselves offer smaller bandwidths than those of SiGe DACs. In [17], transmitter with three CMOS DACs for each dimension has been demonstrated to generate 200-GBaud signals achieving net data rates of 1.58 Tbps back-to-back and 1.50 Tbps after 21-km transmission.

The function of the analog electronics to extend the bandwidth can also be implemented in the optical domain. This approach can significantly relax the bandwidth requirements for the electronics and electro-optic converters. However, conventional frequency-interleaving schemes rely on optical demultiplexing filters [18, 19], which occupy large space and make the system highly sensitive to wavelength misalignment. Recently we have reported a

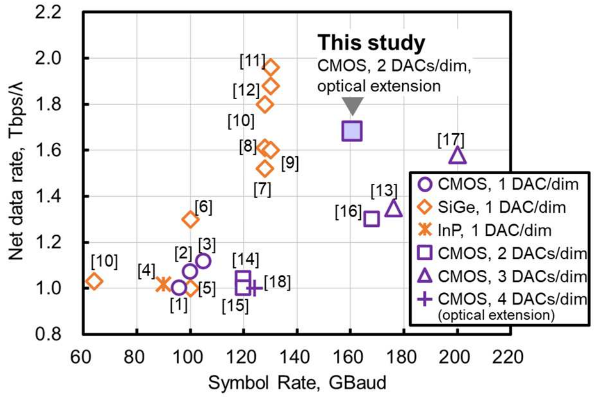

Fig. 1: Overview of recently demonstrated optical transmitters operating at net ≥1 Tbps/λ.

bandwidth-extending transmitter utilizing an optical time-interleaving in-phase-and-quadrature modulator (TI-IQM) [20], which is much simpler and colorless (wavelength-insensitive). However, data rates exceeding 1 Tbps with such simplified optical bandwidth-extending transmitters has been yet to be achieved.

In this paper, we report a novel optical bandwidth-extending transmitter consisting of an 8×4 digital spectral weaver (DSW), CMOS DACs, and an InP integrated phase-interleaving (PI-) IQM. We demonstrate net data rates of 1.68 Tbps back-to-back and 1.64 Tbps after 80-km transmission at a symbol rate of 160.7 GBaud.

Principle

For simplicity, here we consider a case of single-polarization IQ modulation where each DAC generates a signal with a bandwidth of B. We use two DACs for each of the I and Q dimensions to generate arbitrary optical signals with total bandwidths of $4B$ ($2B$ for each sideband), which is twice that of a single-DAC/dimension system with the same DACs.

As shown in the right of Fig. 2, the PI-IQM consists of a differential phase modulator (DPM)

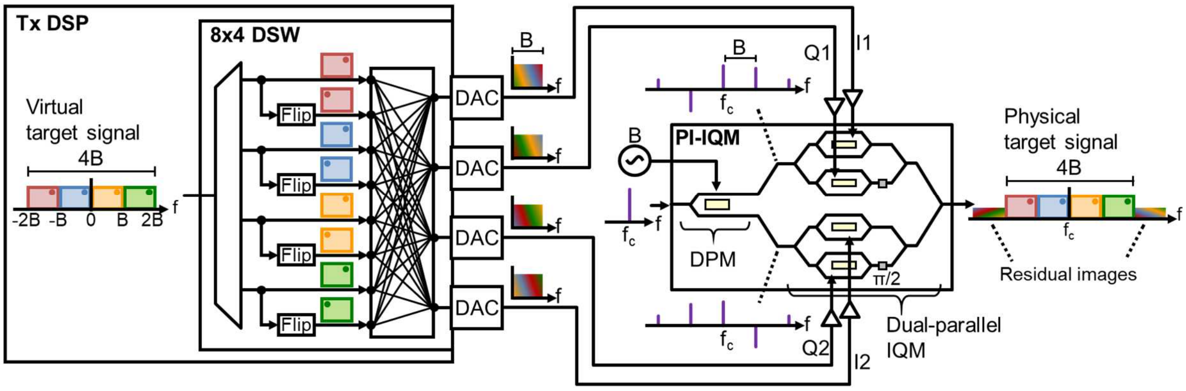

Fig. 2: Principle of bandwidth extension using the PI-IQM and the 8×4 DSW.

driven at a frequency of *B* and a dual-parallel IQM driven by the signals from the DACs. The only difference from the TI-IQM [19] is that the 2×2 coupler at the output of the phase modulators is missing, making the optical circuit simpler. The number of differential phase modulators and the colorless nature of the circuit (no optical filters included) are unchanged. The input waveforms to the two parallel IQMs in the PI-IQM have alternating optical phases, rather than alternating intensity as in the TI-IQM. (In this sense, we should call these as phase-TI-IQM and intensity-TI-IQM, respectively, but let us employ the simpler terms.) When the optical carrier frequency is f_c, each of the two waveforms has spectral lines at f_c, $f_c \pm B$, $f_c \pm 2B$, …, whose relative intensities depend on the driving amplitude. The phases at $f_c \pm B$ relative to those at f_c differ by π between the two waveforms. The convolution of the DACs' outputs and those lines spans beyond the optical bandwidth of 4*B*.

To generate the signals to be sent to the DACs, we use the 8×4 DSW shown in the left of Fig. 2. The DSW is a natural extension of those used in [16, 20] to the complex modulation. It virtually separates the target complex signal with a total bandwidth of 4*B* into four spectral slices, each with a bandwidth of *B*. Then, the slices and their spectrally flipped copies (those with inverted frequencies and conjugated complex amplitudes) are fed to an 8×4 filter. Nonlinear pre-distortion can also be done at this stage. The filter's coefficients are determined so that the physical (analog) target signal is synthesized through interference of the two IQMs' outputs. Thus, we can generate arbitrary optical signals with a total bandwidth up to 4*B* despite the DACs' bandwidth constraint of *B*. Residual images also appear on both sides of the target signal but can be easily removed during or after the transmission.

Experiments

We fabricated the PI-IQM by using the n-p-i-n InP modulator platform [21]. We monolithically

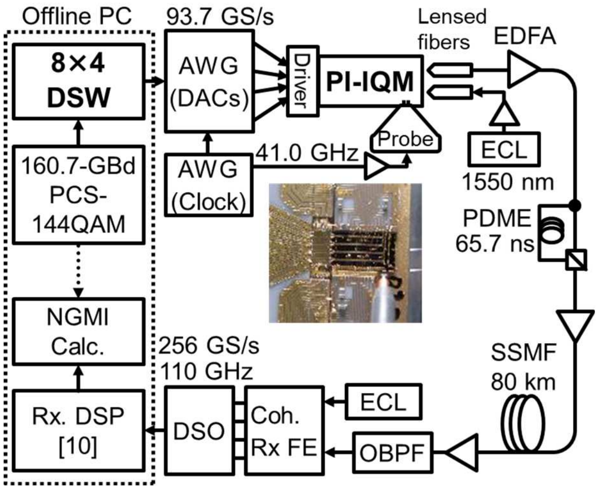

Fig. 3: Experimental setup.

integrated the DPM and dual-parallel IQM in a 3×5-mm^2 chip with a U-turn layout. The chip was then mounted on a temperature controlling evaluation board, where a four-channel driver amplifier [22] was wire-bonded to the dual-parallel IQM. The clock to drive the DPM was supplied by using an RF probe. A pair of spherical lensed fibers fixed to moving stages were used to input and output the light. The optical insertion loss including fiber coupling losses is 7.5 dB at a wavelength of 1550 nm, when all the DC biases are aligned to give the minimum loss.

Fig. 3 shows the setup for the transmission experiment. We used an offline PC and 93.7-GS/s arbitrary waveform generator (AWG) based on CMOS DACs to emulate the digital signal processor (DSP) and DACs, respectively. Another AWG is used to generate the clock to drive the DPW. We set *B* to 41.0 GHz. An external-cavity laser (ECL) supplied 1550-nm CW light to the modulator. The output of the modulator was amplified by an erbium-doped fiber amplifier (EDFA) before being input to a polarization-division-multiplexing emulator (PDME) with a 65.7–ns delay line. The PDM signal was transmitted over 80-km standard single-mode fiber (SSMF), EDFAs, and an optical

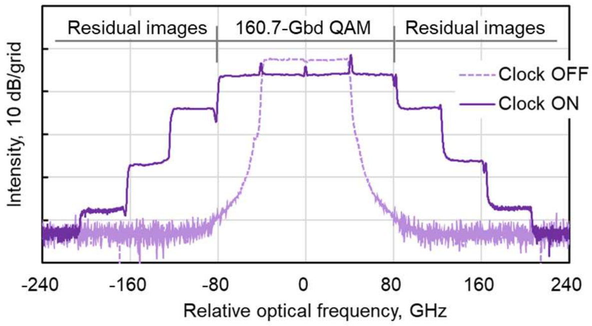

Fig. 4: Optical signal spectra measured at the output of PI-IQM.

band-pass filter (OBPF). The signal was finally received by a coherent receiver frontend followed by a 256-GS/s 110-GHz digital storage oscilloscope (DSO). The coefficients of the DSW were optimized by using test signals in advance. Then, we sent 160.7-GBaud probabilistically constellation-shaped 144-level quadrature amplitude modulation (PCS-144QAM) signals each with a length of ~3×10^5 symbols. The pilot overhead (OH) was set to 1.63%. We used different seeds of the random number generator (Mersenne Twister) for the test and target signals to avoid overfitting. The data rate was varied by changing the entropy of the Maxwell-Boltzmann distribution of the transmitted symbols. On the receiver side, we used basically the same offline DSP as [10], which includes a frequency-domain 8×2 adaptive equalizer with an FFT block size of 4,096. We finally calculated normalized generalized mutual information (NGMI) as the performance metric.

Fig. 4 shows optical signal spectra measured at the output of the PI-IQM. The horizontal axis is the frequency relative to the optical carrier frequency. When the 41-GHz clock to drive the DPM was off, the signal bandwidth was 41 GHz on each side of the carrier. When it was on, the spectrum was extended to around 80.4 GHz on each side, accompanied by the residual images on both sides. In Fig.5, the measured NGMIs are plotted against the net data rate, which was calculated assuming the use of a forward error-correction (FEC) code with a code rate of 0.826 and an NGMI threshold of 0.857 [16]. When the entropy per 4D symbol is H, the net data rate is $\{H-(1-0.826)\times16\}/1.0163\times0.1607$ Tbps. The maximum net data rates with NGMIs better than the threshold were 1.68 Tbps (H = 13.41) and 1.64 Tbps (H = 13.16) at back to back and after 80-km transmission, respectively.

Conclusion

We have demonstrated an optical bandwidth-extending transmitter based on a PI-IQM and an 8×4 DSW, achieving net data rates of 1.68 and 1.64 Tbps at back to back and after 80-km SSMF transmission, respectively. The PCS-144QAM signals at a high symbol rate of 160.7 GBaud were generated using two 93.7-GS/s CMOS DACs for each signaling dimension.

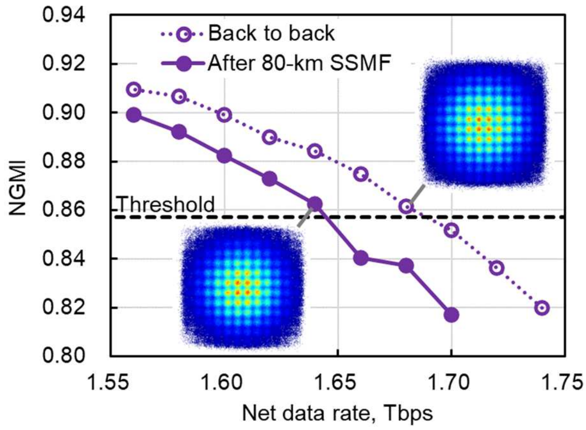

Fig. 5: Measured NGMI vs. net data rate.

References

[1] A. Matsushita, M. Nakamura, S. Yamamoto, F. Hamaoka and Y. Kisaka, "41-Tbps C-Band WDM Transmission With 10-bps/Hz Spectral Efficiency Using 1-Tbps/λ Signals," *Journal of Lightwave Technology*, vol. 38, no. 11, pp. 2905-2911, 2020, DOI: 10.1109/JLT.2020.2986083

[2] F. Buchali, V. Lauinger, M. Chagnon, K. Schuh and V. Aref, "CMOS DAC Supported 1.1 Tb/s/λ DWDM Transmission at 9.8 bit/s/Hz Over DCI Distances," *Journal of Lightwave Technology*, vol. 39, no. 4, pp. 1171-1178, 2021, DOI: 10.1109/JLT.2020.3034575

[3] D. Che and X. Chen, "Achievable Rate Comparison between Probabilistically- Shaped Single-Carrier and Entropy-Loaded Multi-Carrier Signaling in a Bandwidth-Limited 1-Tb/s Coherent System," presented at *Optical Fiber Communication Conference (OFC'21),* San Francisco, CA, USA, 2021, paper M3H.5, DOI: 10.1364/OFC.2021.M3H.5

[4] G. Raybon, A. Adamiecki, J. Cho, P. Winzer, A. Konczykowska, F. Jorge, J-Y. Dupuy, M. Riet, B. Duval, K. Kim, S. Randel, D. Pilori, B. Guan, N. Fontaine, and E. C. Burrows, "Single-carrier all-ETDM 1.08-Terabit/s line rate PDM-64-QAM transmitter using a high-speed 3-bit multiplexing DAC," *in Proceedings of 2015 IEEE Photonics Conference (IPC)*, Restron, VA, USA, 2015, pp. 1-2, DOI: 10.1109/IPCon.2015.7323760

[5] K. Schuh, F. Buchali, W. Idler, T. A. Eriksson, L. Schmalen, W. Templ, L. Altenhain, U. Dümler, R. Schmid, M. Möller, and K. Engenhardt, "Single carrier 1.2 Tbit/s transmission over 300 km with PM-64 QAM at 100 GBaud," presented at *Optical Fiber Communication Conference (OFC'17)*, Los Angeles, CA, USA, 2017, paper Th5B.5, DOI: 10.1364/OFC.2017.Th5B.5

[6] F. Buchali, K. Schuh, R. Dischler, M. Chagnon, V. Aref, H. Buelow, Q. Hu, F. Pulka, M. Frascolla, E. Alhammadi, A. Samhan, I. Younis, M. El-Zonkoli, and P. Winzer, "1.3-Tb/s single-channel and 50.8-Tb/s WDM transmission over field-deployed fiber," presented at *European Conference on Optical Communication (ECOC'19)*, Dublin, Ireland, 2019, paper PDP1.3, DOI: 10.1049/cp.2019.1017

[7] F. Buchali, V. Aref, M. Chagnon, K. Schuh, H. Hettrich, A. Bielik, L. Altenhain, M. Guntermann, R. Schmid, and M. Möller, "1.52 Tb/s Single Carrier Transmission Supported by a 128 GSa/s SiGe DAC," presented at *Optical Fiber Communication Conference (OFC'20)*, San Diego, CA, USA, 2020, paper Th4C.2, DOI: 10.1364/OFC.2020.Th4C.2

[8] V. Bajaj, F. Buchali, M. Chagnon, S. Wahls and V. Aref, "Single-channel 1.61 Tb/s Optical Coherent Transmission Enabled by Neural Network-Based Digital Pre-Distortion," presented at *European Conference on Optical Communication (ECOC'20)*, Brussels, Belgium, 2020, paper Tu1D.5, DOI: 10.1109/ECOC48923.2020.9333267

[9] F. Pittalà, R-P. Braun, G. Boecherer, P. Schulte, M. Schaedler, S. Bettelli, S. Calabrò, M. Kuschnerov, A. Gladisch, F-J. Westphal, C. Xie, R. Chen, Q. Wang, and B. Zheng, "Single-Carrier Coherent 930G, 1.28T and 1.60T Field Trial," presented at *European Conference on Optical Communication (ECOC'21)*, Bordeaux, France, 2021, paper, Th2C1.1, DOI: 10.1109/ECOC52684.2021.9605966

[10] M. Nakamura, T. Kobayashi, F. Hamaoka, and Y. Miyamoto, "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 Proceedings of Optical Fiber Communication Conference (OFC'22)*, San Diego, CA, USA, 2022, paper M3H.1

[11] M. Xu, Y. Zhu, F. Pittalà, J. Tang, M. He, W. C. Ng, J. Wang, Z. Ruan, X. Tang, M. Kuschnerov, L. Liu, S. Yu, B. Zheng, and X. Cai, "Dual-polarization thin-film lithium niobate in-phase quadrature modulators for terabit-per-second transmission," *Optica,* vol. 9, no. 1, pp. 61-62, 2022, DOI: 10.1364/OPTICA.449691

[12] F. Pittalà, R-P. Braun, G.Böcherer, P. Schulte, M. Schaedler, S. Bettelli, S. Calabrò, M. Kuschnerov, A. Gladisch, F-J. Westphal, C. Xie, R. Chen, Q. Wang, and B. Zheng, "1.71 Tb/s Single-Channel and 56.51 Tb/s DWDM Transmission Over 96.5 km Field-Deployed SSMF," *IEEE Photonics Technology Letters*, vol. 34, no. 3, pp. 157-160, 2022, DOI: 10.1109/LPT.2022.3142538

[13] X. Chen, S. Chandrasekhar, G. Raybon. S. Olsson, J. Cho, A. Adamiecki, and P. Winzer, "Generation and Intradyne Detection of Single-Wavelength 1.61-Tb/s Using an All-Electronic Digital Band Interleaved Transmitter," *in Proceedings of Optical Fiber Communication Conference (OFC'18)*, San Diego, CA, USA, 2018, paper Th4C.1, DOI: 10.1364/OFC.2018.Th4C.1

[14] M. Nakamura, F. Hamaoka, M. Nagatani, H. Yamazaki, T. Kobayashi, A. Matsushita, S. Okamoto, H. Wakita, H. Nosaka, and Y. Miyamoto, "1.04 Tbps/Carrier Probabilistically Shaped PDM-64QAM WDM Transmission Over 240 km Based on Electrical Spectrum Synthesis," *in Proceedings of Optical Fiber Communication Conference (OFC'19)*, San Diego, CA, USA, 2019, paper M4I.4, DOI: 10.1364/OFC.2019.M4I.4

[15] T. Kobayashi, M. Nakamura, F. Hamaoka, M. Nagatani, H. Wakita, H. Yamazaki, T. Umeki, H. Nosaka, and Y. Miyamoto, "35-Tb/s C-Band Transmission Over 800 km Employing 1-Tb/s PS-64QAM Signals Enhanced by Complex 8 × 2 MIMO Equalizer," *in Proceedings of Optical Fiber Communication Conference (OFC'19)*, San Diego, CA, USA, 2019, paper Th4B.2, DOI: 10.1364/OFC.2019.Th4B.2

[16] M. Nakamura, F. Hamaoka, H. Yamazaki, M. Nagatani, Y. Ogiso, H. Wakita, M. Ida, A. Matsushita, T. Kobayashi, H. Nosaka, and Y. Miyamoto, "1.3-Tbps/carrier net-rate signal transmission with 168-GBaud PDM PS-64QAM using analogue-multiplexer-integrated optical frontend module," *in Proceedings of European Conference on Optical Communication (ECOC'19)*, Dublin, Ireland, 2019, paper Tu.2.D.5, DOI: 10.1049/cp.2019.0845

[17] X. Chen, G. Raybon, D. Che, J. Cho and K. W. Kim, "Transmission of 200-GBaud PDM Probabilistically Shaped 64-QAM Signals Modulated via a 100-GHz Thin-film LiNbO3 I/Q Modulator," *in Proceedings of Optical Fiber Communication Conference (OFC'21),* San Francisco, CA, USA, 2021, paper F3C.5, DOI: 10.1364/OFC.2021.F3C.5

[18] R. Rios-Müller, J. Renaudier, P. Brindel, H. Mardoyan, P. Jennevé, L. Schmalen, and G. Charlet, "1-Terabit/s net data-rate transceiver based on single-carrier Nyquist-shaped 124 GBaud PDM-32QAM," *in Proceedings of Optical Fiber Communication Conference (OFC'15),* Los Angeles, CA, USA, 2015, paper, Th5B.1, DOI: 10.1364/OFC.2015.Th5B.1

[19] T. Henauer, A. Sherifaj, C. Füllner, W. Freude, S. Randel, T. Zwick, and C. Koos, "200 GBd 16QAM Signals Synthesized by an Actively PhaseStabilized Optical Arbitrary Waveform Generator (OAWG), " *in Proceedings of Optical Fiber Communication Conference (OFC'22)*, San Diego, CA, USA, 2022, paper M2I.2

[20] H. Yamazaki, M. Nakamura, T. Goh, T. Hashimoto and Y. Miyamoto, "Extension of Transmitter Bandwidth Using Optical Time-Interleaving Modulator and Digital Spectral Weaver," *Journal of Lightwave Technology*, vol. 39, no. 4, pp. 1132-1137, 2021, DOI: 10.1109/JLT.2020.3041034

[21] Y. Ogiso, J. Ozaki, Y. Ueda, H. Wakita, M. Nagatani, H. Yamazaki, M. Nakamura, T. Kobayashi, S. Kanazawa, Y. Hashizume, H. Tanobe, N. Nunoya, M. Ida, Y. Miyamoto, and M. Ishikawa, "80-GHz Bandwidth and 1.5-V Vπ InP-Based IQ Modulator," *Journal of Lightwave Technology*, vol. 38, no. 2, pp. 249-255, 2020, DOI: 10.1109/JLT.2019.2924671

[22] T. Jyo, M. Nagatani, Y. Ogiso, S. Yamanaka and H. Nosaka, "An Over 67-GHz Bandwidth 21-dB Gain 4.5-Vppd Linear Modulator Driver for 100-GBd Coherent Optical Transmitter," *IEEE Microwave and Wireless Components Letters*, vol. 31, no. 6, pp. 705-708, 2021, DOI: 10.1109/LMWC.2021.3062423