Optical Phase-Interleaving Transmitter for 1.6-Tbit/s/λ Digital Coherent Systems Based on CMOS DACs

Hiroshi Yamazaki
Netowrok Innovation Labs /Device Technology Labs
NTT Corporation
Yokosuka/Atsugi, Japan
hiroshi.yamazaki.mt@hco.ntt.co.jp

Yoshihiro Ogiso
Device Innovation Center
NTT Corporation
Atsugi, Japan
yoshihiro.ogiso.uv@hco.ntt.co.jp

Masanori Nakamura
Network Innovation Labs
NTT Corporation
Yokosuka, Japan
masanori.nakamura.cu@hco.ntt.co.jp

Teruo Jyo
Device Technology Labs
NTT Corporation
Atsugi, Japan
zhaonan.xu.ew@hco.ntt.co.jp

Munehiko Nagatani
Network Innovation Labs /Device Technology Labs
NTT Corporation
Yokosuka/Atsugi, Japan
munehiko.nagatani.uh@hco.ntt.co.jp

Josuke Ozaki
Device Innovation Center
NTT Corporation
Atsugi, Japan
josuke.ozaki.mp@hco.ntt.co.jp

Takayuki Kobayashi
Network Innovation Labs
NTT Corporation
Yokosuka, Japan
takayuki.kobayashi.wt@hco.ntt.co.jp

Toshikazu Hashimoto
Device Technology Labs
NTT Corporation
Atsugi, Japan
toshikazu.hashimoto.ur@hco.ntt.co.jp

Yutaka Miyamoto
Network Innovation Labs
NTT Corporation
Yokosuka, Japan
yutaka.miyamoto.fb@hco.ntt.co.jp

***Abstract*—By using a bandwidth-extending transmitter with an 8×4 digital spectral weaver, CMOS DACs, and an optical phase-interleaving modulator, we achieved transmission at net bit rate beyond 1.6-Tbit/s/λ.**

Keywords—Digital coherent, bandwidth extension, DAC, digital spectral weaver, phase interleaving, InP modulator

I. Introduction

There is a growing demand for high-speed data transmission technologies as bandwidth-hungry applications, such as 5G mobile service, the Internet of Things, and virtual reality, become more widespread. It is important to increase data rate per wavelength channel in wavelength-division-multiplexing (WDM) optical networks so that the ever-increasing data traffic are efficiently accommodated. As shown in Fig. 1, many digital coherent transmission experiments with net bit rates of 1 Tbps or more per wavelength channel have been reported recently. The performance of digital-to-analog converters (DACs) in the transmitter is a key factor in achieving such high bit rates. Si complementary metal oxide semiconductor (CMOS) DACs are widely used in current commercial systems because they can be monolithically integrated with digital signal processors (DSPs). With CMOS DACs in a conventional configuration, where one DAC is used in each signaling dimension (in-phase, I, and quadrature, Q, of each polarization channel), net rates around 1 Tbit/s/λ have been achieved [1]-[3]. However, the moderate analog bandwidth of CMOS DACs have made it difficult to achieve higher bit rates. InP [4] and SiGe [5]-[17] DACs offer larger bandwidth in general, and net bit rates beyond 1.6 Tbit/s/λ have been achieved with SiGe DACs in the conventional one-DAC-per-dimension configuration [8]-[13]. Furthermore, up to 2.1 Tbit/s/λ have been achieved by using two SiGe DACs time-interleaved with a baseband 2:1 combiner in each dimension [13]-[17]. However, from a practical point of view, connecting those compound DACs with the DSP is considered to be highly challenging. To overcome the bandwidth constraint while using CMOS DACs, bandwidth-extension technologies have also been employed

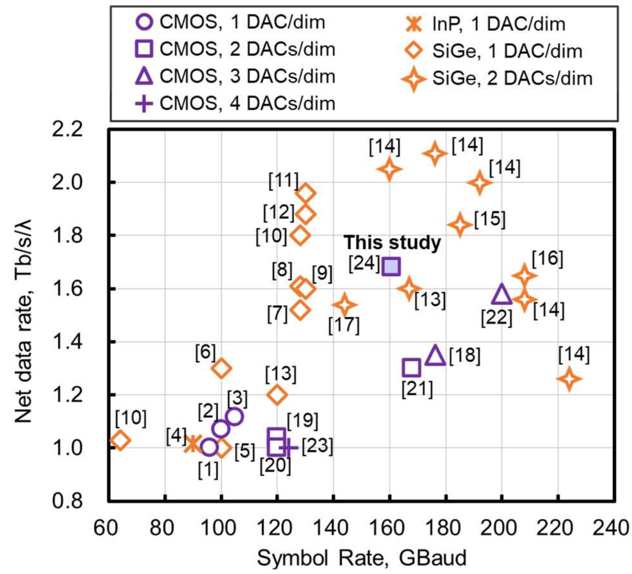

Fig. 1. Overview of recently reported digital coherent optical transmission experiments with net bit rates of 1 Tbit/s/λ or higher based on a single continuous-wave (CW) laser.

in the Tbit/s/λ experiments [18]-[24]. In those approaches, multiple DACs are used in each dimension, and clock-driven analog electronics [18]-[22] or optics [23], [24] are used to generate intermediate-frequency (IF) images of those DACs' outputs. In combination with digital pre-processing algorithms, the transmitter generates arbitrary signals exceeding the analog bandwidth of each DAC. The bandwidth-extension technologies are different from the baseband interleaving [13]-[17], which does not extend the bandwidth in essence but just enables us to utilize the spectral component beyond the Nyquist frequency of the DACs.

In this invited paper, we review our recent experiment on a bandwidth-extending transmitter with two DACs in each dimension, an InP optical phase-interleaving IQ modulator

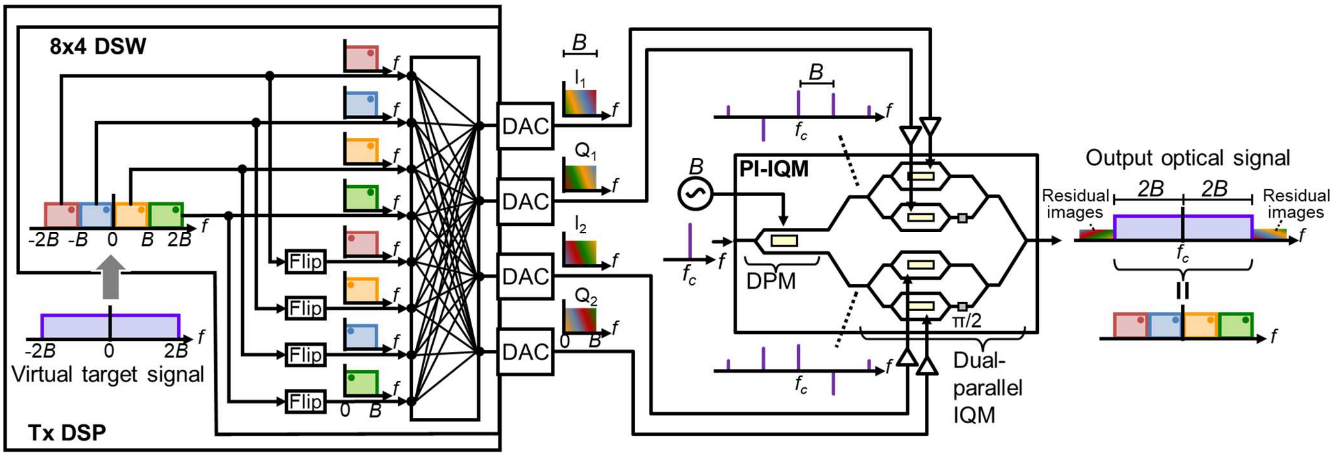

Fig. 2. Principle of bandwidth extension using an optical PI-IQM and an 8×4 DSW.

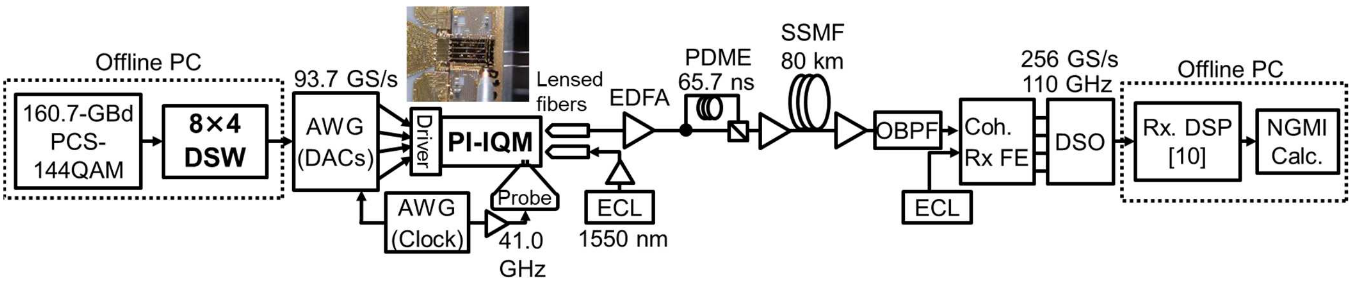

Fig. 3. Experimental setup.

(PI-IQM), and an 8×4 digital spectral weaver (DSW). We achieved net bit rates beyond 1.6 Tbit/s/λ for the first time with a transmitter based on CMOS DACs [24].

II. Principle

The principle of bandwidth extension is shown in Fig. 2 [24]. A single-polarization configuration is shown for simplicity. Here, we have DACs with a bandwidth of B, while we want to generate arbitrary optical signals with bandwidths up to $2B$ on each side of the optical carrier at a frequency of f_c. To achieve this, we first virtually "fold" the target signal in the DSW so that all the information is carried by multiple sub-signals, each with a bandwidth of B. After making the sub-signals go through the DACs (two for each dimension), we "unfold" the sub-signals through generation and superposition of the IF images in the PI-IQM to obtain the final output signal corresponding to the target signal.

To explain the principle in detail, we start from the PI-IQM, in which a differential phase modulator (DPM) is followed by a dual-parallel IQM. The DPM is equivalent to a push-pull Mach-Zehnder modulator without an output coupler, and is driven by a clock signal at a frequency of B to generate two output waveforms with alternating optical phases. In the frequency domain, the outputs of the DPM are mainly composed of f_c and $f_c{\pm}B$ components, and the phases at $f_c{\pm}B$ relative to those at f_c differ by π between the two outputs. The IQMs are driven with the signals from the DACs, and their outputs include the fundamental components and the first-order images of the driving signals at around f_c and $f_c{\pm}B$, respectively. By combining the outputs from the two IQMs, we obtain the final output signal spanning $f_c{\pm}2B$. This process can be interpreted as a superposition of the DACs' outputs and their spectrally flipped copies within each of B-spaced spectral slices of the final output, and is analytically invertible under practical conditions [24]. Based on this insight, in the DSP before the DACs, we virtually generate the target signal and divide it into four spectral slices, each with a bandwidth of B. Then, we use those slices and their spectrally flipped copies as the input to the DSW, which actually is an 8×4 finite-impulse-response (FIR) filter acting as an inverse system of the PI-IQM. The DSW can also include nonlinear pre-distortion filters. Thus, we can arbitrarily control the waveform of the final optical output signal within the spectral region of $f_c{\pm}2B$, while our DACs has a bandwidth of only B. As for the region outside $f_c{\pm}2B$, we have residual images originating from the higher-order components in the DPM's outputs, but those images can be easily filtered out during or after the transmission.

The principle explained above is a generalization of the bandwidth extension in real-valued domain [25]-[27] to the complex domain. Compared to the optical time (intensity) interleaving (TI) [27], the optical configuration of the PI is slightly simpler in that the 2×2 coupler after the DPW is missing. Unlike the conventional frequency interleaving [23], [28], the PI, as well as TI, is advantageous in that it is colorless (independent of the input optical wavelength) at the circuit level.

III. Experiments

The setup for the experimental demonstration of the bandwidth extension using the PI-IQM and 8×4 DSW is shown in Fig. 3. The DSP and the array of DACs were emulated by an offline PC and a 93.7-GS/s CMOS-DAC-based benchtop arbitrary waveform generator (AWG, Keysight M8196A), respectively. The PI-IQM was fabricated by using our in-house n-p-i-n InP modulator platform [29], [30]. The DPM and dual-parallel IQM are monolithically integrated in a 3×5-mm^2 chip with a U-turn layout. A four-channel driver amplifier [31] to drive the IQMs is wire-bonded to the PI-IQM chip on an evaluation board equipped with a temperature controller, RF coaxial connectors, and DC connectors. We used an RF probe to input the clock to the DPM. To input and output the light, we used a pair of spherical lensed fibers attached to moving stages. The PI-IQM's optical insertion loss at a wavelength of 1550nm was 7.5 dB including fiber coupling losses, when all DC biases are adjusted to minimize the loss. The clock at a frequency of 41.0 GHz was supplied from another AWG, which is also used as the source clock for the DAC-emulating AWG. As the transmitter light source and the local oscillator (LO), we used CW external-cavity lasers (ECLs). The PI-IQM was followed by an erbium-doped fiber amplifier (EDFA) and a polarization-division-multiplexing emulator (PDME) with a delay line of 65.7 ns. The signal was then transmitted over standard single-mode fiber (SSMF) with a length of 80 km and another EDFA with an optical band-pass filter (OBPF). The receiver consisted of a coherent receiver frontend, a 256-GS/s 110-GHz digital storage oscilloscope (DSO), and an offline DSP including an 8×2 frequency-domain adaptive equalizer, which is basically the same as those used in [10], with an FFT block size of 4096. Finally, as the performance metric, normalized generalized mutual information (NGMI) was calculated assuming the use of a soft-decision forward error-correction (SD-FEC) code with a code rate of 0.826 and an NGMI threshold of 0.857 [32].

Before transmitting the payload signal, we first transmitted a test signal to optimize the weighs of the DSW in the offline DSP. After that, we virtually generated 160.7-GBaud probabilistically constellation-shaped 144-level quadrature amplitude modulation (PCS-144QAM) signals and sent it to the DSW. We set the signal length to around 3×10^5 symbols with a pilot overhead (OH) of 1.63%. The PCS-144QAM signals were generated from random sequences generated by the Mersenne Twister with different seeds from those used for the test signal. The entropy, H, of the Maxwell-Boltzmann distribution of the PCS-144QAM signal was varied.

Optical signal spectra measured at the output of the PI-IQM are shown in Fig. 4, where the horizontal axis is the frequency relative to f_c. When the clock to drive the DPM is off, a spectrum with a bandwidth of 41 GHz on each side of f_c was observed, reflecting the spectra of the DACs' output signals. On the other hand, when the clock is on, a spectrum with nearly-doubled bandwidth with residual images on both sides was observed, as expected. Fig. 5 shows the NGMIs at various H. The NGMIs beyond the threshold were obtained up to H=13.41 and H=13.16 for 0 (back-to-back) and 80-km transmissions, respectively. Since the net bit rate is $\{H-(1-0.826)\times16\}/1.0163\times0.1607$ Tbps, we can conclude the signals at net bit rates of 1.68 and 1.64 Tbps were successfully transmitted for 0 and 80-km SSMF.

IV. Conclusion

Using a bandwidth-extension technology with two DACs for each signaling dimension, a PI-IQM, and an 8×4 DSW, we can overcome the bandwidth constraint of the CMOS DACs and achieve per-wavelength net bit rates beyond 1.6 Tbit/s. This technology is promising for efficient accommodation of high-speed client signals in the future.

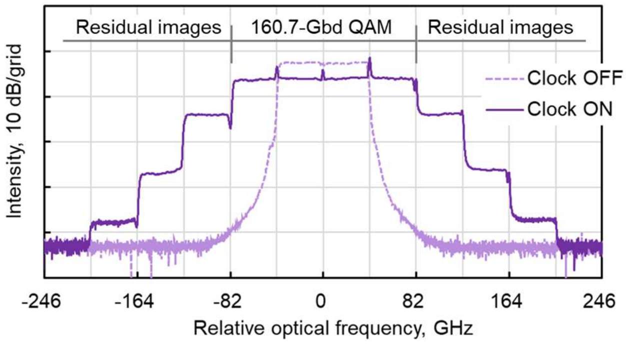

Fig. 4. Optical signal spectra measured at the output of PI-IQM.

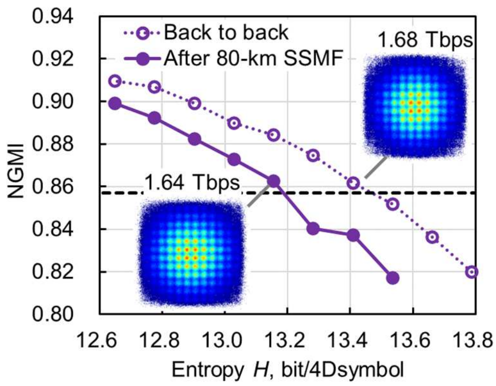

Fig. 5. Measured NGMI vs. entropy H.

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