Digital-preprocessed Analog-multiplexed Digital-to-analog Converter for Ultrahigh-speed Optical Transmitter

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Abstract

We have developed technology to extend the analog bandwidth of digital-to-analog converters (DACs), which are essential in advanced high-speed optical transmitters. We used a digital preprocessor, two sub-DACs, and an analog multiplexer to generate arbitrary signals with a bandwidth nearly twice that of each sub-DAC. This technology was used to successfully demonstrate various high-speed transmissions, including an intensity-modulated directly detected transmission at a record-high data rate of 250 Gbit/s.

Keywords: DSP, DAC, analog multiplexer

1. Introduction

The continued growth of data traffic in communications systems has resulted in the need to find ways to increase data rates of optical transmission systems [1]. Digital signal processors (DSPs) play key roles in current high-speed transmission systems [2, 3]. Functions of the DSPs include high-order modulation, pulse shaping, equalization, and dispersion compensation, which are essential for achieving high data rates with high spectral efficiency.

In a DSP-based transmitter, the analog bandwidth of digital-to-analog converters (DACs) is a key factor to determine the achievable data rate. The DACs used in commercial transmitters today are fabricated on silicon complementary metal-oxide semiconductor (CMOS) platforms and integrated with DSPs monolithically [2, 3]. Those CMOS DACs have a rather moderate analog bandwidth of ~30 GHz, which is one of the factors limiting the data rate.

DACs based on compound platforms such as indium phosphide (InP) or SiGe (silicon-germanium) provide larger bandwidth [4–6], but they consume more power. Compound DACs also pose some implementation challenges because the DSP will continue to be based on CMOS technology. This is why there is a strong need to develop technologies to extend the bandwidth using existing CMOS DACs.

We have developed a digital-preprocessed analog-multiplexed DAC (DP-AM-DAC) that is a promising potential solution in this context [7–10]. The DP-AM-DAC consists of a digital preprocessor, two sub-DACs, and an analog multiplexer (AMUX) and functions as a DAC with an analog bandwidth of almost twice that of each sub-DAC. We have generated signals with bandwidths of up to ~60 GHz with CMOS

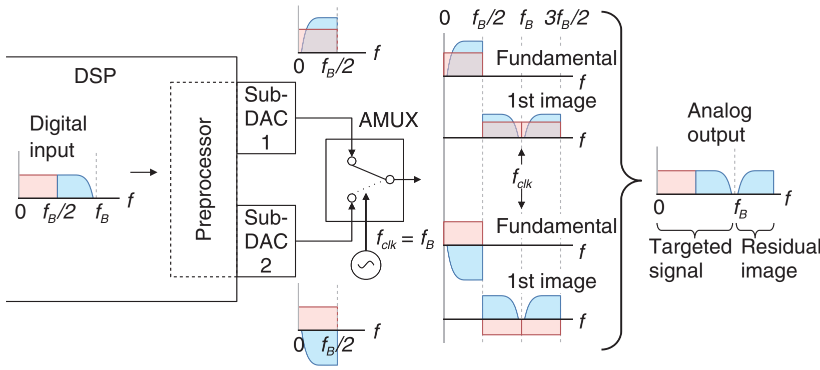

Fig. 1. Configuration and principle of DP-AM-DAC (type I).

sub-DACs and an AMUX based on an InP heterojunction bipolar transistor (HBT). Unlike other bandwidth-extension technologies that use analog mixers [3, 11], the DP-AM-DAC has a symmetric configuration with respect to the two sub-DACs and so makes it easier to balance the two branches. In this article, we review our DP-AM-DAC and the high-speed transmission experiments conducted with it.

2. Principle

The configuration and principle of the DP-AM-DAC is shown in **Fig. 1**. It consists of a digital preprocessor, two sub-DACs, and an AMUX [7–10]. When the bandwidth of the sub-DACs is $f_B/2$, we can obtain an arbitrary signal with a bandwidth up to around f_B (twice that of the sub-DACs) as the final output from the AMUX. The schematic spectra in Fig. 1 represent the principle of the DP-AM-DAC, in which the AMUX is driven at $f_{clk} = f_B$ [7].

First, the digital representation of the target signal with a bandwidth up to f_B is input to the preprocessor. The preprocessor weaves the information of the target signal into two digital sub-signals with a corresponding bandwidth of $f_B/2$ or less so that the sub-DACs can handle them without loss of information. Specifically, the preprocessor separates the input signal into low- and high-frequency components—respectively represented by red and blue—and then flips the high-frequency component around $f_B/2$ in the frequency domain. Finally, the processor adds the flipped high-frequency component to the low-frequency component with a specific amplitude ratio and complementary phases to make the two respective sub-signals.

The sub-DACs convert the digital sub-signals into the analog sub-signals, which pass alternately through the AMUX at a clock frequency of f_{clk}. In the frequency domain, this alternation, or multiplexing, corresponds to a superposition of the sub-signals themselves and their images (up-converted copies) generated around f_{clk}, where the phases of the images for the two sub-signals are complementary to each other. As seen in Fig. 1, the superposition results in the reconstruction of the target signal in the frequency region of $0 < f < f_B$. The residual image of the high-frequency component in the frequency region of $f_B < f < 3f_B/2$ can be removed by a low-pass filter. The principle explained above is what we call the type-I DP-AM-DAC. We have also developed the type-II model, which has the same hardware configuration as the type-I model but uses a different preprocessing algorithm so that we can reduce the required f_{clk} by half and suppress the residual image [8].

3. AMUX characteristics

The key component in the DP-AM-DAC is the AMUX, which we designed and fabricated using our in-house 0.5-µm-emitter InP HBT technology [12]. As mentioned above, the AMUX is a linear high-speed selector that makes two input signals pass through it alternately at the clock frequency without any regeneration. Time-domain waveforms we measured to verify the AMUX are shown in **Fig. 2**. We input a 1-GHz sinusoidal wave to one input port while applying direct current (DC) voltage to the other and varied the clock frequency. The obtained output waveforms show that the AMUX selects the two inputs alternately at the clock frequency, as designed.

The static frequency responses of the AMUX module

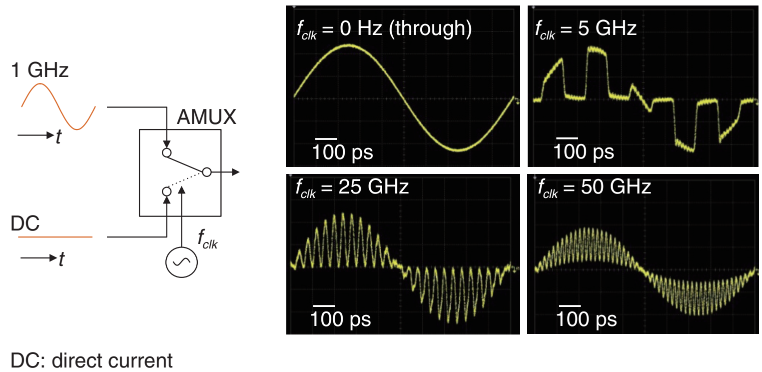

Fig. 2. Time-domain waveforms output from the AMUX multiplexing a 1-GHz sinusoidal wave and DC voltage at clock frequencies of 0, 5, 25, and 50 GHz.

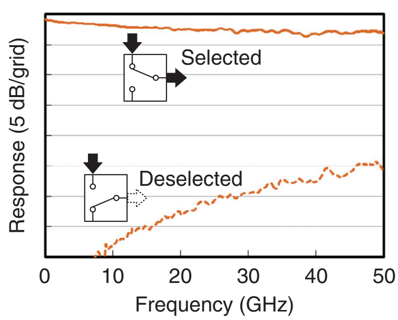

Fig. 3. Static frequency responses of AMUX when the input signal is selected and deselected.

are shown in **Fig. 3**. The response is measured by applying DC voltage to the clock port to select and deselect the input analog signal under test to measure the through and isolation characteristics, respectively. Up to the measured frequency range of 50 GHz, the through loss is less than 3 dB, while the isolation (the difference between the two curves) is more than 20 dB.

4. Transmission results

The DP-AM-DAC was first demonstrated in a high-speed intensity-modulated direct-detection (IMDD) transmission, in which we employed Nyquist-shaped 80-Gbaud (160-Gbit/s) four-level pulsed amplitude modulation (PAM4) [7]. The experimental setup is shown in **Fig. 4**. We used two channels of a CMOS-based arbitrary waveform generator (AWG) as the sub-DACs with an analog 3-dB bandwidth of ~20 GHz. The signal was generated using the type-I DP-AM-DAC at f_{clk} = 43.3 GHz. As the optical transmitter, we used an O-band (1.3-μm) externally modulated laser with a modulation bandwidth of > 55 GHz [13]. The optical signal was transmitted over 20-km standard single-mode fiber (SSMF) and then amplified by a fiber amplifier and received by a photodiode. The DSP, including the preprocessor of the DP-AM-DAC, the receiver-side filter, and an adaptive equalizer (AEQ) was emulated by an offline personal computer.

The electrical spectra of the output signals from the two sub-DACs and the AMUX are shown in **Fig. 5(a)–(c)**. Although the signals from the sub-DACs have a bandwidth of only ~22 GHz, that from the AMUX includes a rectangular waveform with a bandwidth of ~40 GHz, which corresponds to the target 80-Gbaud Nyquist PAM4 signal. The residual image at > 46 GHz observed in the AMUX output was removed by the receiver-side matched filter in this experiment.

The eye diagram of the 80-Gbaud (160-Gbit/s) PAM4 signal after transmission over 20-km SSMF and through the digital matched filter and the AEQ is shown in **Fig. 6**. The bit error rate (BER) was 6.2 x 10^{-3}. This result corresponds to the net data rate of 142.9 Gbit/s, assuming the use of 12%-overhead (OH) hard-decision forward error correction (FEC) code [14].

We also demonstrated a higher net data rate of 250 Gbit/s with the type-II DP-AM-DAC [8]. The setup was similar to the one shown in Fig. 4, but the sub-DACs (AWG) were upgraded to those with an analog 3-dB bandwidth of ~32 GHz, and the f_{clk} was changed to 37.5 GHz. With the type-II principle, we can generate signals with the analog bandwidth up to

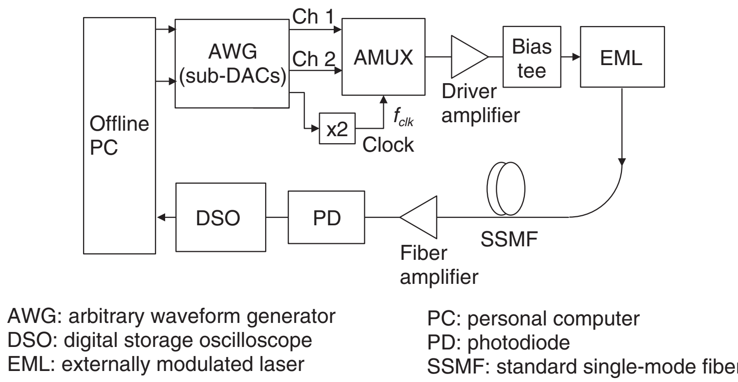

Fig. 4. Experimental setup for high-speed IMDD transmission experiments using the DP-AM-DAC.

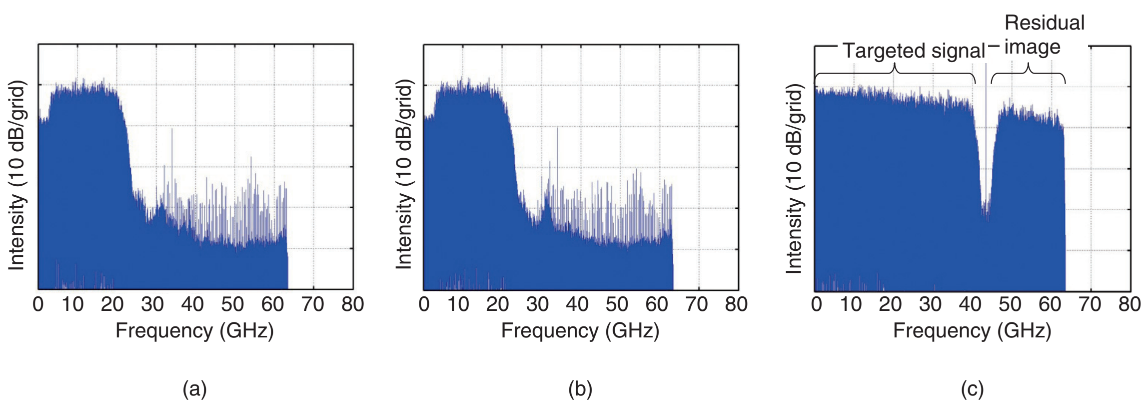

Fig. 5. Electronic spectra of output signals from (a) sub-DAC channel 1, (b) sub-DAC channel 2, and (c) AMUX measured in the 80-Gbaud PAM4 transmission experiment.

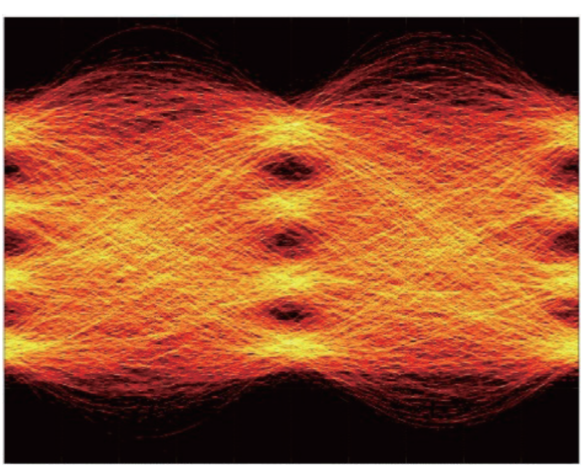

Fig. 6. Eye diagram of 80-Gbaud PAM4 signal after 20-km SSMF transmission and digital AEQ.

$2f_{clk}$ = 75 GHz, although the bandwidth used in the experiment was limited to 62 GHz by the bandwidth of the DSO (digital storage oscilloscope). We employed discrete multitone (DMT) modulation [15] to efficiently utilize the available bandwidth. The electronic spectrum and constellations of the received DMT signal at the total bit rate of 300.12 Gbit/s after transmission over 10-km SSMF are shown in **Fig. 7**. The total BER was 2.63 x 10^{-2}, which is lower than the threshold of the 20%-OH soft-decision FEC code [16], and it corresponds to the transmission at a net data rate of 250 Gbit/s.

In addition to the results described above, we have reported various high-speed transmission experiments utilizing DP-AM-DACs, including long-haul digital coherent transmission [17–20].

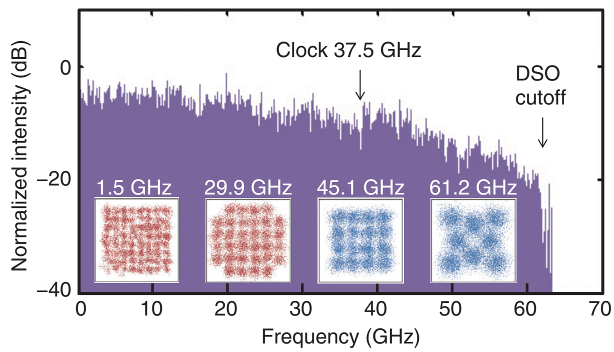

Fig. 7. Electronic spectrum and constellations of the 300.12-Gbit/s DMT signal after 10-km SSMF transmission.

5. Conclusion

With the DP-AM-DAC, we can overcome the bandwidth limitation imposed by the analog bandwidths of CMOS DACs. The combination of the digital preprocessor, two CMOS sub-DACs, and the high-speed AMUX enables us to generate arbitrary signals with a bandwidth nearly twice that of each sub-DAC. This technology is promising for use in future ultrahigh-speed optical transmitters for various application fields, including short-reach IMDD and long-haul digital coherent systems.

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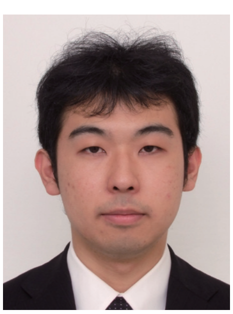

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