Transmitter Bandwidth Extension Using Optical Time-Interleaving Modulator and Digital Spectral Weaver

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Abstract: We generate 150-Gbaud QAM signals by using an optical time-interleaving modulator driven with 38.1-GHz-bandwidth sub-signals. A digital spectral weaver enables generation of arbitrary bandwidth-extended signals with a simple filter-less optical configuration.

1. Introduction

To meet ever-growing demand for high-speed data communications services, high-modulation-order and high-symbol-rate transmission technologies are extensively studied [1]. High-speed digital-to-analog converters (DACs) are indispensable to generate high-modulation-order signals, but their analog bandwidths are the major factors that restrict the achievable symbol rate. Since DACs' analog bandwidths are not expected to scale drastically, bandwidth-extension technologies using parallel DAC architectures with additional analog electronics are attracting a lot of attention [1-3]. On the other hand, bandwidth extension can also be achieved in the optical domain [4, 5]. Although the optical approaches require higher hardware complexities, they are less challenging in terms of scaling the final output bandwidth. The combination of the electronic and optical syntheses will also be promising.

Frequency interleaving (FI) with digital spectral slicing has been employed in both electronic [3] and optical [4, 5] bandwidth extension schemes. Time interleaving (TI) with digital spectral weaving has also been demonstrated as a method of electronic bandwidth extension [1, 2], but has not yet been brought into the optical domain.

In this paper, we report the first demonstration of the TI-based optical bandwidth extension. We show the digital spectral weaver originally designed for an electronic analog multiplexer (AMUX) [1, 2] can also be used with an optical TI modulator to generate arbitrary signals with a bandwidth of each sideband up to twice that of the DACs. The merit of the TI over FI is its filter-less operation, which makes the device simpler. To verify the concept, we fabricated an integrated optical TI modulator and drove it with a 38.1-GHz switching clock and spectrally weaved sub-signals to generate 150-GBaud QPSK, 8QAM, and 16QAM signals.

2. Principle

Fig. 1 shows the principle of the bandwidth extension for coherent transmission using the optical TI concept. The principle is essentially analogous to that of the bandwidth extension using an electronic analog multiplexer (AMUX) [1, 2]. To make the figure simple, only in-phase (I) components of the signals are represented. The same principle applies to the quadrature (Q) components. We assume we want to generate an optical signal with a bandwidth of each sideband of $2B$, but our DACs can generate signals with a bandwidth of only B. We use an integrated TI-IQ modulator (TI-IQM) consisting of an optical selector (quadrature-biased dual-output MZM) driven at a switching frequency of $f_{SW} = B$ and a dual-parallel IQM driven by the DACs generating sub-signals with a bandwidth of B. As shown in the middle, the two outputs from the selector are alternating sinusoidal waves, which have three major spectral lines at f_c (optical carrier frequency) and $f_c \pm B$ with complementary relative phases. The sub-signals to drive the IQMs are defined by the spectral weaver in the transmitter DSP (Tx DSP). The weaver virtually separates the target signal into low- and high-frequency components (represented in red and blue, respectively) at a boundary of B and superimposes those components with specific phase and amplitude relationships. The spectra of the IQMs' outputs are the convolutions of the three lines (f_c and $f_c \pm B$) and the sub-signals, and have a bandwidth of each sideband of $2B$. The two IQMs' outputs are finally combined together, where all components other than those of the target signal disappear by reversed-phase interference (the weaver is designed so that this happens). Thus, we can obtain arbitrary optical waveforms with a bandwidth of each sideband up to $2B$, which is twice the DACs' analog bandwidth and corresponds to the maximum symbol rate of $4B$. Unlike the conventional 2OTDM [6], in which the final output symbol rate is limited to $2f_{SW}$, the TI with spectral weaving allows us to flexibly set the symbol rate up to $4f_{SW}$ (= $4B$). This principle can also be extended to a dual polarization IQM by doubling the number of IQMs and adding a polarization multiplexing circuit after the IQMs.

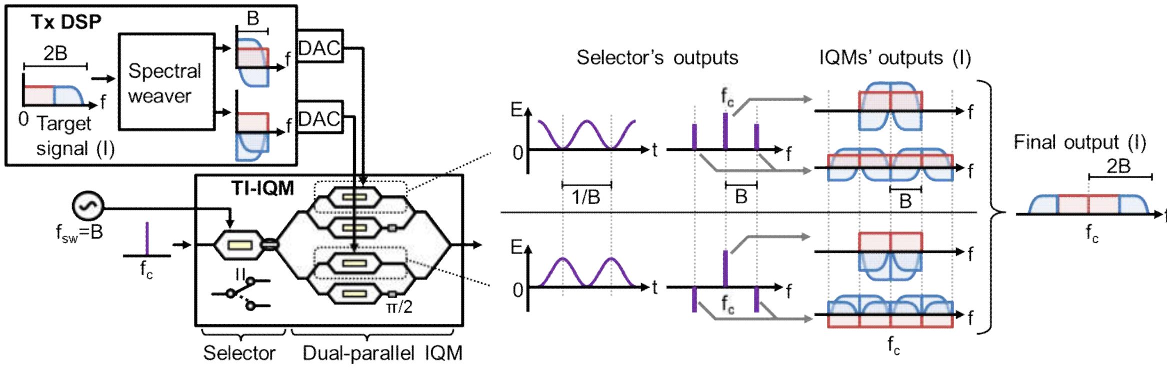

Fig. 1. Principle of bandwidth extension using the TI-IQM and the digital spectral weaver. To make the figure simple, only the I-component signals are shown. The same principle applies to the Q-component.

Fig. 2 compares the hardware complexity of FI and TI configurations assuming the same target bandwidth of $2B$ and the DACs' bandwidth of B. As shown in Fig. 2(a), the conventional FI uses a subcarrier (SC) generator MZM followed by a de-multiplexing (DEMUX) filter [9]. In general, a DEMUX filter occupies a large space in the circuit and allows only fixed frequency gap between the subcarriers ($2B$ in this case). Fig. 2(b) is a FI configuration using a complementary frequency shifter (CFS), with which we can eliminate the DEMUX filter [10]. However, the CFS itself is a dual-parallel clock-driven MZM and is more complicated than the SC generator. (The same complexity issue applies to the carrier-suppressed TDM reported in [11].) On the other hand, the TI configuration used in this study requires only a single selector MZM before the IQMs while using no DEMUX filters, as shown in Fig. 2(c).

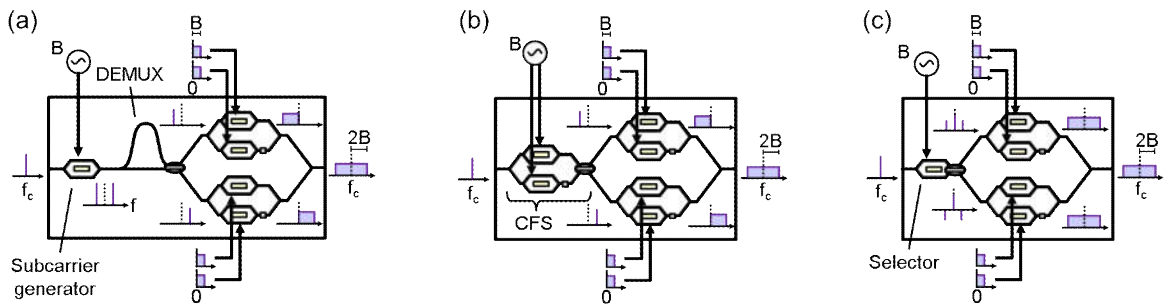

Fig. 2. Configurations for (a) conventional FI, (b) FI with a CFS, and (c) TI used in this study.

3. Experiments

As shown in Fig. 3(a), we fabricated an integrated TI-IQM by using a hybrid integration of silica planar lightwave circuits (PLCs) and a $LiNbO_3$ phase-modulator array [10, 11]. The selector MZM and the dual-parallel IQM were connected by a pair of U-turn waveguides with the same length. One of the two PLCs has thermo-optic (TO) phase shifters for optical-phase adjustment. The total footprint of the hybrid chip is 115 x 8 mm. When all the phase shifters are adjusted to maximize the output power, the total optical insertion loss of the module is 9.9 dB. Electro-optic bandwidth and V_π of each MZM are around 23 GHz and 6V, respectively. Fig 3(b) shows the back-to-back single-polarization digital coherent setup to test the TI-IQM. The DSP, DACs, and ADCs were emulated by an offline PC, a 93.7-GS/s benchtop arbitrary waveform generator (AWG), and a 256-GS/s 113-GHz digital storage oscilloscope (DSO), respectively. The 3-dB analog bandwidth of the AWG (DACs) was around 32 GHz. Another AWG was used as a clock source to supply a 38.1-GHz switching clock to the TI-IQM. Two tunable light sources (TLSs) with a wavelength of 1550 nm and a linewidth of <100-kHz were used as the transmitter laser and the receiver local oscillator. An amplified spontaneous emission (ASE) source was used to control the optical signal-to-noise ratio (OSNR). A polarization controller (PC), an optical 90-degree hybrid, and a couple of 100-GHz balanced photodiodes (BPDs) were used to receive the optical signals. Imbalances between the sub-channels and impact of spurious images were compensated for in the offline Tx DSP. In the receiver-side DSP, we used a 61-tap finite-impulse-response adaptive equalizer (AEQ) before calculating the bit-error rate (BER). We set Nyquist-shaped 150-Gbaud QPSK and QAM signals conveying random data generated by a Mersenne twister as the target signals.

Fig. 4(a) shows optical signal spectra of the output signals from the TI-IQM. The horizontal axis is the frequency relative to the optical carrier frequency. When the selector was not driven (OFF), the spectrum reflected the driving signals' bandwidth of 38.1 GHz on each side of the carrier. When the selector was driven (ON), the spectrum was extended smoothly up to around 76 GHz on each side, although the optical power severely decayed toward high relative frequency due to the low 3-dB bandwidth of the LN. A step observed in the frequency region of >76 GHz on each side corresponds to the second-order spurious image, whose impact on the main signal was mitigated in the Tx DSP. Figs. 4(b-d) are the BER vs OSNR curves of the 150-GBaud QPSK, 8QAM, and 16QAM signals, respectively. Assuming the use of 25.5%-overhead (OH) soft-decision forward error correction (SD-FEC) code [12], net data rates for the three formats are 239, 359, and 478 Gbps, respectively. The OSNR penalties from the theoretical curves were around 3.0 and 6.4 dB for 8QAM and 16QAM, respectively, at the "threshold" BER of the 25.5%-OH SD-FEC of 3.7×10^{-2} [12].

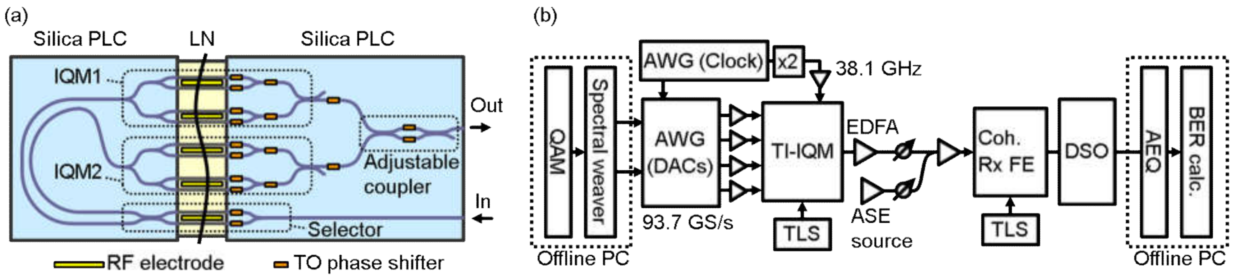

Fig. 3. (a) Configuration of the TI-IQM. (b) Experimental setup.

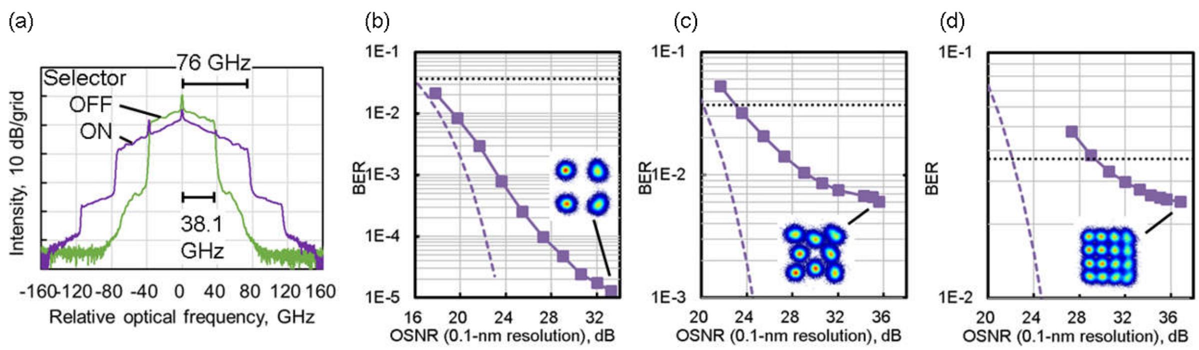

Fig. 4. (a) Optical signal spectra measured at the output of TI-IQM. (b-d) BER vs OSNR curves for 150-Gbaud QPSK, 8QAM, and 16QAM. Constellations, theoretical BER curves (dashed lines), and the threshold of 25.5%-OH SD-FEC (dotted lines) are also shown.

3. Conclusion

Using TI with digital spectral weaving, we can optically extend bandwidth of a DAC-based transmitter with a simple optical configuration. The concept was verified by using an integrated TI-IQM with a silica-LN hybrid configuration to generate 150-GBaud QAM signals. Higher symbol rates will be achievable by employing other modulator platforms, such as InP [13], which provides much higher EO performances.

4. Acknowledgement

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