Electro-optic synthesis of multi-level coherent signals

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Abstract
We propose an electro-optic vector digital-to-analogue converter employing a structure of multi-parallel Mach-Zender modulator. We demonstrate synthesis of high-speed and high-spectral-efficient optical multi-level coherent signals like n-PSK, n-QAM etc, by superposing BPSK signals.

Introduction
Optical multi-level formats ultimately improve spectral efficiency of optical transmission channels. Several formats such as quadrature phase-shift-keying (QPSK) including differential quadrature phase-shift-keying (DQPSK) [1-3], amplitude- and phase-shift-keying (APSK) [4], quadrature-amplitude-modulation (QAM) [5-10], etc, are now intensively investigated. To generate these multi-level signals in a transmitter side, orthogonal modulation using vector modulator is a typical way. However, it is difficult to achieve high-bit-rate operation because the technology relies on electric multi-level signaling.

In this paper, we propose an electro-optic vector digital-to-analogue converter (EO-DAC) as an alternative approach, which enables synthesis of such high-order optical multi-level signals at higher bit rate. In the technology, multi-level signals are synthesized as a superposition of binary PSKs by using a novel structure of multi-parallel MZM. By the EO-DAC, we can synthesize high-order multi-level signals in several modulation formats without handling multi-level electric signals, which is advantageous for high-bit-rate operation. In this paper, we review experimental demonstration of synthesis of 8PSK and 16QAM signals.

Electro-optic vector digital-to-analogue conversion
For synthesis of coherent multi-level signals, original digital signals should be mapped onto phaser plane of an optical carrier. There are typically two approaches. One is the approach based on optical IQ modulator which realizes orthogonal modulation on in-phase and quadrature components of the input lightwave. In this approach, a pair of multi-level electric signals converted from binary data sequences is introduced into the IQ modulator. In this case, a pair of digital-to-analogue converters (DACs) is required to generate the multi-level signals and the electric analogue channel between the DAC and the modulator should be carefully managed to transmit the multi-level electric signal without degradation.

The other approach is based on an EO-DAC, as we propose in this paper. In this approach, QAM signal is synthesized from binary electric signals by using a multi-parallel modulator. In each arm of the modulator, BPSK is generated by the MZM. Controlling optical amptiude and phase offset between the BPSKs correctly, multi-level coherent signals in 2^n level can be synthesized as a superposition of n sets of the BPSKs. Note that the binary data sequences injected in parallel to the modulator are directly mapped onto the optical carrier in an electro-optic manner. This means that the modulator plays a role of vector DA conversion; hence electric DACs are not required. This is advantageous for synthesis of coherent multi-level signals at high bit rate since electronic device and components dealing with binary data streams are matured well. In addition, signal level of each symbol can be less fluctuated owing to rectification characteristics of the MZM. If we increase the number of MZMs employed in the multi-parallel modulator, arbitrary modulation formats can be synthesized.

Synthesis of multi-level modulation formats
Here, we discuss synthesis of multi-level modulation formats, concentrating on the case of n=4. At present, it is not so easy to develop multi-parallel MZMs with n>>4 for EO-DAC with higher resolution. In this case, the modulator employed should have four MZMs integrated, which is called quad-parallel MZM (QPMZM). Fig. 1

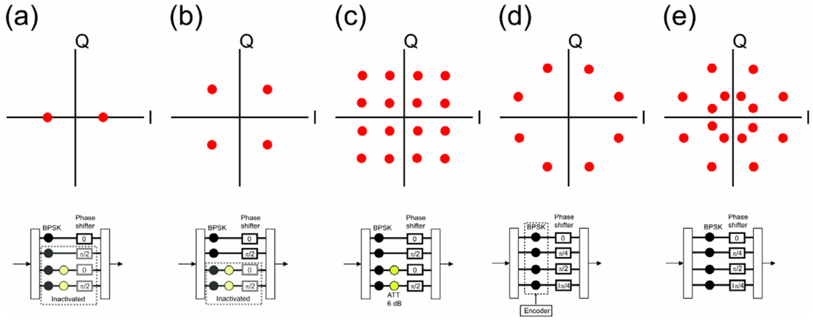

Fig. 1. Synthesis of multi-level modulation formats using 4-bit EO-DAC; (a) BPSK, (b) QPSK, (c) 16QAM, (d) 8PSK, (e) APSK(-like)

shows the examples of modulation formats synthesized with the EO-DAC with n=4. BPSK and QPSK can be, of course, generated if undesired MZMs are turned off (Fig. 1(a), (b)).

Fig. 1(c) shows the operation mode for synthesis of 16QAM. In this case, phase offset between the BPSK created in each arm ($BPSK_1$, $BPSK_2$, $BPSK_3$, $BPSK_4$,) is set at $\phi_1 = 0$, $\phi_2 = \pi/2$, $\phi_3 = 0$, $\phi_4 = \pi/2$; amplitude of each BPSK is set at $a_1 = 1$, $a_2 = 1$, $a_3 = 1/2$, $a_4 = 1/2$. Two QPSK with different amplitudes are generated by the combination of [$BPSK_1$, $BPSK_2$] and [$BPSK_3$, $BPSK_4$], respectively. 16 QAM can be synthesized by superposing the two QPSK signals.

Other multi-level modulation formats are available if the EO-DAC is operated under different condition. As shown in Fig. 1(d), an APSK(-like) signal can be synthesized if $\phi_1 = 0$, $\phi_2 = \pi/4$, $\phi_3 = \pi/2$, $\phi_4 = 3\pi/4$; $a_1 = a_2 = a_3 = a_4 = 1$, where 16 symbols are arranged in a radial form in a phaser plane. Selecting the outermost symbols, 8PSK is also generated from the EO-DAC (Fig. 2(d)). Note that such multi-level modulation formats are synthesized from binary data sequences without handling multi-level electric signals.

Experiments

In this section, we experimentally demonstrate synthesis of 8PSK and 16QAM by the use of 4-bit EO-DAC [7]. Experimental setup is shown in Fig. 2(a).

In the 4-bit EO-DAC, 4 sets of NRZ sequences were electro-optically converted to 8PSK/16QAM. Therein, a CW light generated from an external cavity laser diode was externally modulated with the QPMZM. Each arm of the modulator was push-pull driven with 12.5-Gb/s (or 10-Gb/s) binary NRZ data with the length of 2^{15}-1 PRBS, which was generated from a typically used 4-ch pulse pattern generator. The QPMZM in the 4-bit EO-DAC, has a hybrid integrated structure of $LiNbO_3$ waveguide modulators and silica-based planner lightwave circuits (PLC), where the input and output of the modulator section were butt jointed with the PLC based optical splitters, as shown in Fig. 2 in Ref. 7.

The signal generated from the EO-DAC was demodulated with a digital homodyne receiver, [3], where the signal light was mixed with a local oscillator (LO) light by using an optical 90-degree hybrid coupler. The hybrid coupler gave the 90-degree phase offset between its four output ports, and by balanced photo detection of the [0^o, 180^o] and [90^o, -90^o] pairs, I and Q components of the signal projected to the LO were recovered. The photodetected signals were introduced into high speed AD converters and phase difference between the signal and LO was estimated by digital signal processing.

Figs. 2 (a)-(c) shows the constellation maps for synthesis of 8PSK [11]. Firstly, we activated two of the MZMs in the QPMZM to check whether the MZMs in the QPMZM structure were operated well and the optical phase differences between the arms were correctly assigned. Fig. 2(a) is a constellation map obtained when

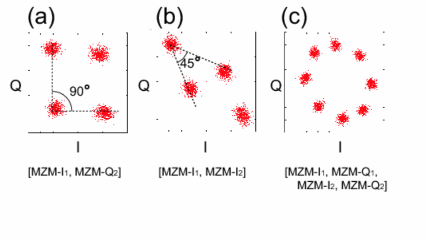

Fig. 2. Synthesis of 8PSK

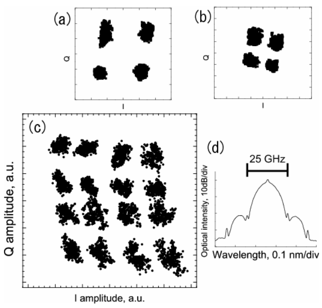

Fig. 3. Synthesis of 16QAM

the pair of [$BPSK_1$, $BPSK_3$] was activated. It is found that the optical phase difference between the activated arms was ~$\pi/2$ and QPSK was generated in this operation mode. Fig. 2(b) indicates the constellation map monitored when the pair of [$BPSK_1$, $BPSK_2$] was activated. In this case, the optical phase difference between the arms was ~$\pi/4$. After the preparatory experiments, all of the MZMs were turned on. As shown in Fig. 2(c), an 8 PSK signal was successfuly synthesized.

Fig. 3 is the results for synthesis of 16QAM. Fig. 3 (a) shows the constellation map obtained when $BPSK_1$ and $BPSK_2$ were activated, whereas Fig. 3 (b) is the case when $BPSK_3$ and $BPSK_4$ were activated. It can be seen that large-amplitude and small-amplitude QPSK signals were generated, respectively. Fig. 3 (c) shows the IQ map obtained when all of the MZMs were activated. It is confirmed that 16 QAM was successfully generated as the superposition of two QPSKs.

Conclusions

In this paper, we have proposed an electro-optic vector digital-to-analogue converter for synthesis of optical multi-level coherent signals. We have reviewed synthesis of n-PSK, n-QAM signals.

References

[1] K. Ishida et al, OFC’04, FM2 (2004)
[2] M. Daikoku et al, OFC’06, PDP36 (2006)
[3] S. Tsukamoto, et al, OFC’05, PDP29 (2005)
[4] N. Kikuchi, et al, OFC’07, PDP21 (2007),
[5] M. Nakazawa, *et al*, OFC’07, PDP26 (2007)
[6] A. Chiba et al, OECC'07, 12B3-4 (2007)
[7] T. Sakamoto, et al, ECOC’07, PD2.8 (2007)
[8] Y. Mori et al, ECOC'08, Tu.1.E.4 (2008)
[9] M. Nakamura *et al*, ECOC'08, Tu.1.E.5 (2008)
[10] P. Winzer and A.H. Gnauck, ECOC'08, Th.3.E.5 (2008).
[11] T. Sakamoto, *et al*, OFC’09, OTuG4 (2009)