# Optical Single-Sideband (SSB) Conversion Technique Using Phase Modulator for High-Speed Short-Reach IM/DD PAM Signaling

**Nobuhiko Kikucih, Riu Hirai and Takahito Tanimura**
*Research & Development Group, Hitachi Ltd. 1-280 Higashi-Koigakubo, Kokubunji, Tokyo 185-8601*
*nobuhiko.kikuchi.ca@hitachi.com*

**Abstract:** We propose novel SSBI-free SSB conversion technique of high-speed PAM signals by phase modulation and show improvement of CD tolerance of MZ and EML transmitter by >6 and >7.6 times in 40-GB PAM4 transmission experiments.

## 1. Introduction

Data traffic within and between data centers grows very rapidly, and spurs the needs for ultra high-speed short-reach optical fiber links, such as 400GbE and beyond. In terms of cost and simplicity, intensity-modulation/directly-detection (IM/DD) is the mainstay of short reach links, and PAM4 signaling is introduced to realize 50- and 100-Gbit/s/Lambda-class links in 400GbE [1][2]. Meanwhile, its signaling speed is increased to 26 and 53 GBaud, and further increase to 100 GBaud is considered in 800G. Since such increase of signaling speed changes the limiting factor of transmission reach from the fiber loss to the fiber chromatic dispersion (CD), therefore improvement of CD tolerance of IM/DD PAM signal is an impending problem.

Single sideband modulation (SSB) is a key technique for surpassing CD limit, by suppressing the generation of CD-induced transmission zeros (or frequency dips) in directly-detected channel, and also by the application of optical field reconstruction and CD compensation, by Kramers-Kronig (KK) [3] or iterative techniques [4]. And various optical SSB techniques have been proposed so far [5]: Two major ones are the use of an optical IQ modulator and an narrow optical filter (vestigial side-band modulation, VSB), however the first one has the problem of high modulation/insertion loss (typically 6~10 dB), and the requirement for precise bias control. The latter, also have the problems of high filtering loss (>3 dB) of a sideband and center carrier, and requirement for accurate wavelength tuning. Other approaches using tandem or parallel phase or frequency modulation have been proposed, for example [6][7], but most of them are intended for radio over fiber (RoF), optical frequency domain multiplexed (OFDM) signals, or band-limited applications, and typically not applicable to high-speed baseband PAM signals.

In this paper, we propose baseband optical SSB conversion of IM signal by tandem phase modulation (PM) for high-speed baseband PAM signals to extend its transmission reach, for the first time as far as we know. It is shown to have enough side-mode suppression ratio (SSPR) without signal up-sampling by numerical simulation and experiments, even under tight modulation bandwidth limit. We also demonstrate a chirp cancellation technique for chirped transmitter like EML, which is shown to be effective to improve SSPR and extend transmission reach.

## 2. Principle and Numerical Simulation

The tandem combination of IM and PM can serve as an arbitral field generator, and there is some coordinate and/or encoding options in SSB-PAM signaling. Among them, we choose to encode PAM signal onto the intensity modulation just as conventional dual-sideband (DSB) IM/DD PAM, and use the phase modulation for its SSB conversion; namely, polar-coordinate SSB (PSSB). This configuration has several favorable features for short-reach IM/DD systems: Firstly, it has no theoretical modulation loss against DSB and the insertion loss of a phase modulator is the smallest among various modulators when integrated, which is beneficial for its severely limited power budget. Secondary, the phase modulator is bias-free, unlike IQ modulators. Thirdly, it is signal-signal beat interference (SSBI)-free at low CD and has high affinity to conventional IM/DD-PAM transceivers; for example, most of transmitter specifications and test procedures can be commonly used at back-to-back, and it can disable PM and field reconstruction circuits to save power consumption, if CD is small.

The PM signal for PSSB scheme is the same one introduced in the KK receiver [3][4], that is, $\phi(t)=1/2H[\log(I(t))]$, where $I(t)$ is the signal intensity, H[] stands for the Hilbert transformation. Figure 1 shows the transmitter-side DSP for PSSB modulation, where DC addition and H[Log()] operation is added to the phase modulation path. One possible problem of the proposed scheme is the generation of high-frequency components by the non-linearity in phase modulation; some papers have reported that the KK scheme requires up to four times bandwidth or upsampling to 4~6 sps (samples per symbol) [8]. Also removal techniques of upsampling are proposed [3][8], but they are not applicable to the proposed configuration, since the phase modulation is done externally. To investigate it, we perform numerical simulations of PSSB-PAM4 modulation with the DSP in Fig.1(a) (Nyquist filter with roll-off factor of 0.3), and observe output optical spectra: In Fig.2(a), with electrical modulation bandwidth of Rb (Rb: symbol rate), PSSB with 2-sps DSP shows high SSPR of 42-dB for all over the Nyquist bandwidth (Rb/2) and 4-sps upsampling at H(Log()) operation (PSSB, 4sps) shows only negligible difference. We also test the removal of Log operation, and the highest SSPR by optimizing phase modulation depth is 20 dB. By assuming tighter modulation bandwidth of 0.625 Rb, the SSPR of both 2-sps and 4-sps PSSB are reduced to 31 dB, and that without Log operation is kept the same as in Fig. 2(b). These SSPR values are higher than the ones achieved by practical IQ modulators (~20 dB), and seems to be enough for short-to-intermediate reach applications.

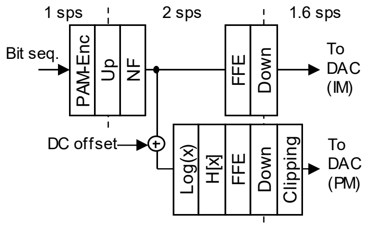


Fig. 1. DSP for Polar-SSB modulation. Up/Down: up-/down-sampling, NF: Nyquist filter, H[]: Hilbert transformation, FFE: Feed-forward equalizer.

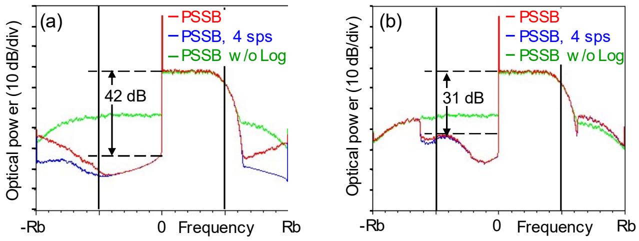


Fig.2 Numerically calculated optical PSSB spectra with rectangular modulation bandwidth limit of (a) Rb and (b) 0.625 Rb on both IM and PM electrical signal paths.

## 3. Experimental Setup and Results

To show the practicality of the PSSB modulation technique, we have performed IM/DD 40-GBaud PSSB-PAM4 signal transmission experiments. Figure 3(a) shows the experimental set up, in which a chirp-less LN Mach-Zehndar (MZ) modulator or an electro absorptive-modulator integrated laser (EML; $\alpha \cong +0.6$) is used as the intensity modulator to generate IM-PAM4 signal, and a following LN-phase modulator is used to convert it to PSSB signal. The extinction ratio of PAM4 signals is set to 5.2 dB (CSPR is 10.3 dB), and we do not perform modulator non-linearity compensation for simplicity. Fiber launching power is set to 0 dBm and an EDFA repeater is used when fiber length exceeds 40 km. The transmitter- and receiver-side DSP are shown in Fig. 1(a) and Fig. 2(b), respectively: We apply 13-tap FFEs for tx-side equalization of both IM and PM signal paths, which mainly compensate DAC low-pass responses. Signal clipping is applied on the PM signal when Log operation is performed to reduce its peak-to-average power ratio (PAPR). The receiver-side DSP has KK-based field reconstruction (4-sps), CD compensation and power detection ($|x|^2$) blocks to evaluate the CD tolerance of the generated PSSB signals. After that we have applied an adaptive Volterra-series FFE (51 linear taps, 2nd and 3rd order taps with channel memory of 7-symbols) mainly to alleviate non-linear distortion by DACs and modulators.

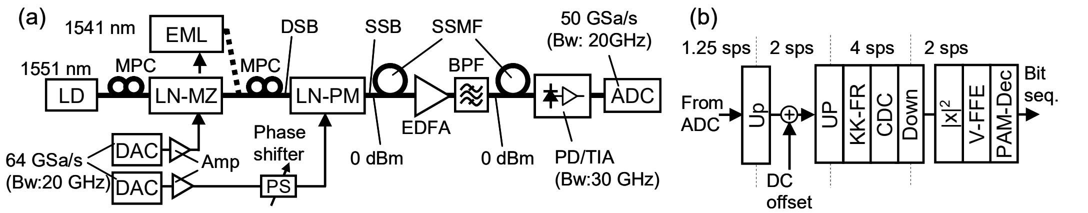


Fig. 3. Schematic diagram of (a) setup and (b) receiver-side DSP of IM/DD 40-GBaud polar-coordinate SSB PAM4 transmission experiments. MPC: manual polarization controller, BPF: Optical band-pass filter, SMF: Standard single-mode fiber, KK-FR: Field reconstruction by KK method, CDC: CD compensation, V-FFE: Volterra non-linear FFE.

Optical spectra of original DSB and converted PSSB signals with phase modulation OFF and ON are shown in Fig. 4(a-d). In Fig. 4(a), the SSPR of PSSB signal based on the LN-MZ is shown to be 22.3 dB; the degradation from the simulation in Fig. 2 is possibly due to the inaccuracy of the Tx-side equalization. It should also be noted that the power of the sideband of PSSB signal becomes 6-dB higher than that of the original DSB signal, which shows its loss-less nature. The SSPR without Log operation is degraded, but still 19.5 dB as in Fig. 4(b). The SSPR of the PSSB signal based on EML is shown to be 19.1 dB in Fig. 4(c), degraded due to its frequency chirp. To mitigate it, we devise EML chirp cancellation (CC); we measure $\alpha$-parameter vs. bias voltage of EML, calculate and subtract chirp component in the PM path of DSP. It is shown to improve the SSPR to 21.1 dB in Fig. 4(d).

The received electrical spectra after 40-km SSMF (CD: 640 ps/nm) is shown in Fig. 4(e) and the frequency dips in DSB are suppressed in PSSB. A back-to-back bit error ratio (BER) curves are shown in Fig. 5, and the difference of those of PSSB and DSB signals is negligible. Experimental eye-patterns and amplitude histograms of PSSB signal with 2-sps DSP at back-to-back and after 40-km SSMF is shown in Fig. 5(a-d) for MZ and EML with CC, and both show still clear four signal levels after KK-reception and CD compensation. The BER vs. CD curves of DSB and PSSB signals are plotted in Fig. 6(e) with the fixed receiving power of -8 dBm. At the BER threshold (4.8E-3) of tandem FEC considered for 800 GbE, the CD tolerance of DSB signal is 130 and 105 ps/nm for MZ and EML. The reach of MZ-PSSB is shown to be extended >6 times beyond 800 ps/nm, and 5.1 times to 670 ps/nm even without Log() operation. That of the EML-PSSB is extended 4.4 timers somewhat degraded by modulator chirp, but it is successfully extended to >7.6 times by the CC technique. It should be noted that the degradation of BER of PSSBs against CD is attributed to the imperfect experimental field modulation or recovery process, but still such improvement of CD tolerance seems to be very effective for beyond 100-GBaud short-reach PAM systems, which typically have CD tolerance of ~10 ps/nm (<10 km in O-band).

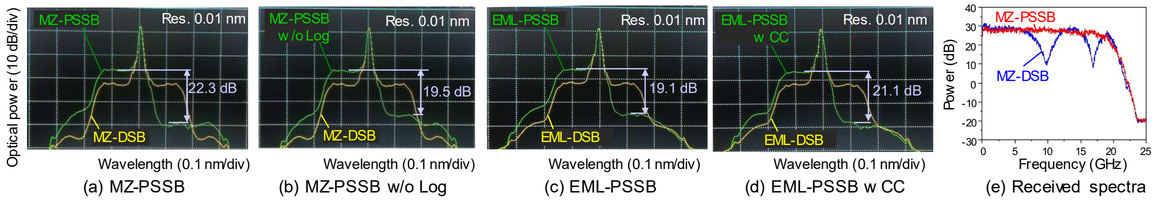


Fig. 4. Experimental transmitter output optical spectra (a-d) and received electrical after 40-km SSMF (e) of 40-GBaud IM/DD DSB and PSSB PAM4 signals.

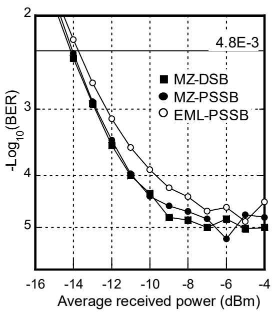


Fig. 5. Back-to-Back BER curves of IM/DD 40-GBaud MZ-DSB, MZ-PSSB and EML-PSSB PAM4 signals.

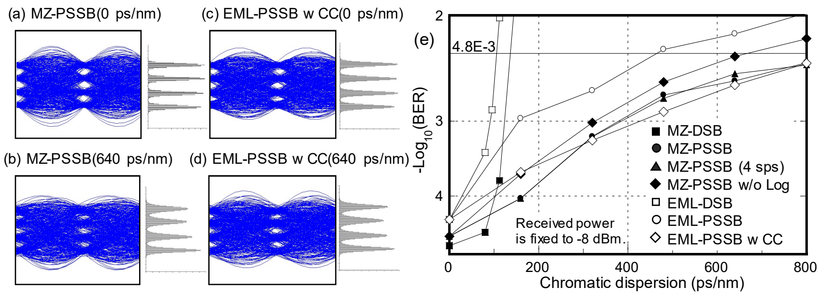


Fig. 6 Experimental fiber transmission performance of 40-GBaud IM/DD DSB and PSSB PAM4 signals: (a-d) received eye-patterns and histograms of MZ- and EML-PSSB at back-to-back and 640 ps/nm, (e) BER against chromatic dispersion.

## 4. Summary

In this paper, we propose SSBI-free polar-coordinate SSB conversion scheme using a tandem phase modulator for short-reach baseband high-speed IM/DD PAM signal, and show that it can extend chromatic-dispersion limited transmission reach of IM/DD-PAM4 signal by >6 times for MZ with KK reception, and >7.6 times for EML also with chirp cancellation.

## 5. References

[1] X. Song *et al.*, "Opportunities for PAM-4 Modulation," IEEE 802.3 400 GbE Study Group, Interium Meeting, Indian Wells, CA, USA, Jan. 2014.
[2] R. Hirai *et al.*, "Proposal of new 400GbE Signaling Formats with 4λ x 100G Configuration," IEEE 802.3 400 GbE Study Group, Interium Meeting, Indian Wells, CA, USA, Jan. 2014.
[3] A. Mecozzi *et al.*, "Kramers–Kronig coherent receiver," *Optica*, Vol. 3, No. 11 pp. 1220–1227, Nov. 2016.
[4] S. T. Le *et al.*, "Optical Single-Sideband Direct Detection Transmissions: Recent Progress and Commercial Aspects," in *Proc. ECOC 2020*, Brussels, Belgium, Dec. 2020, paper Tu1E-1.
[5] T. Bo *et al.*, "Optical Single-Sideband Transmitters," *J. Lightw. Technol.*, vol. 41, no. 4, pp. 1163–1174, Feb. 2023.
[6] T. Bo *et al.*, "Generation of Broadband Optical SSB Signal Using Dual Modulation of DML and EAM," *J. Lightw. Technol.*, vol. 39, no. 10, pp. 3064–3071, May 2021.
[7] C-H. Chang *et al.*, "Optical SSB Modulation Scheme Based on Phase-Modulator and Vertical-Cavity-Surface-Emitting Laser," in *Proc. CLEO 2014*, San Jose, CA, USA, June. 2014, paper STu1J.8.
[8] T. Bo *et al.*, "Kramers-Kronig receiver operable without digital upsampling," *Optics Express*, Vol. 26, No. 11, pp. 13810–13818, May. 2018.