Monolithically Integrable Optical Single Sideband Transmitters for Inter-datacenter Applications

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Abstract: We review the recent research activities on monolithically integrable optical single sideband transmitter schemes for inter-datacenter applications, including monolithic integration of laser with modulator, optical injection-locked laser, and dual modulation of laser and electro-absorption modulator.

1. Introduction

Datacenters (DCs) and their interconnects have become a key infrastructure of our modern society. Although the datacenter has witnessed around 1000-fold data traffic increase in the last decade [1], it is still anticipated that such an explosive increase in data traffic would be continued to support new, diverse, and upcoming data-hungry applications. However, it becomes more and more challenging to scale the capacity of data center interconnects while meeting strict constraints in cost and power consumption. Recently, the inter-DC interconnect attracts a great deal of discussions for its unique requirements. Covering a link distance of tens of kilometers, the inter-DC interconnect experiences non-negligible link loss and fiber chromatic dispersion. Thus, the traditional intensity modulation/direct detection (IM/DD) technique, which dominates the intra-DC applications due to its cost-effectiveness, is not suitable for the inter-DC links. On the other hand, the coherent optics technology is still regarded too expensive for the cost-sensitive application despite its supreme performance.

One feasible solution is the optical single sideband (SSB) transmission with direct detection [2]. It not only overcomes the frequency-dependent power fading problem, but also doubles the spectral efficiency with respect to the conventional double-sideband IM/DD system. The optical SSB system benefits from a much simpler receiver structure (than the coherent receiver), which consists of single photodiode with optional moderate digital signal processing. However, generating optical SSB signal requires complex signal modulation, making the optical SSB transmitter more complicated than that of the traditional IM/DD system. A solution to overcome this challenge and maintain the signal quality simultaneously is the monolithic integration, which integrates the laser and modulator section on the same substrate.

In this paper, we review the recent research trend and progress in the monolithically integrable optical SSB transmitter. The schemes based on monolithic integration of laser with Mach-Zehnder modulator, optical injection-lock laser, and several configurations of electro-absorption laser (EML) are introduced. The merits and the challenges of these schemes are discussed as well. The focus will be on the dually modulated EML scheme. Finally, we show that it is possible to have a compact and energy-efficient optical SSB transmitter with the aid of monolithic integration.

2. Monolithically integrable optical single sideband transmitters

2.1 Monolithic integration of laser with Mach-Zehnder modulator

Indium phosphide (InP) is a key semiconductor material that enables lasers, photodiodes and waveguides to be fabricated on the same substrate and operate at the optimum transmission window of optical fiber. The Mach-Zehnder interferometric structure can be made on the InP substrate as well [3]. This enables the monolithic integration of a coherent transmitter with polarization-multiplexed configuration and even a fully integrated coherent transceiver on a single chip [4]. It is therefore straightforward to use this transmitter optical subassembly (TOSA) for the generation of optical SSB signal. Recently, a couple of experimental demonstrations have been made with this scheme [5],[6]. This transmitter scheme is able to generate high-quality optical SSB signal in terms of the optical sideband suppression ratio (OSSR) and supports a wide range of carrier-to-signal power ratio (CSPR), but it suffers from large number of integrated components (up to >1000) and complicated operation.

2.2 Monolithic optical injection-locked (MOIL) laser

The optical SSB signal can be directly generated from a MOIL laser, as demonstrated in [7]. The MOIL laser consists of a master and a slave laser section grown on the same InP substrate. A typical total length of the MOIL laser sections is 800 μm. When the MOIL works in the injection-locked state, one laser is modulated with signal while the other serves as the optical carrier. This produces an optical SSB signal. Moreover, the resonance frequency of the modulated laser can be enhanced by the injection locking. For example, about 3 times of modulation bandwidth enhancement was observed in [8]. However, direct modulation of the bias current only modulates the optical intensity, which sacrifices half of the usable modulation bandwidth. Another drawback of this scheme is the nonlinear distortion due to the lack of optical isolation between the master and slave laser. Nevertheless, the MOIL laser exhibits several benefits including small footprint and high output power.

2.3 EML

Integrating the InGaAs/InP based distribution feedback laser (DFB) and InGaAs/InAlAs multi-quantum well based electro-absorption modulator (EAM) together makes an EML [9]. EML has the advantages of small size, low power consumption, and high output power, making it one of the most successful photonic integration circuits used in the commercial 2.5/10/40-Gb/s transponders and continue to support the recent >200-Gb/s optical interconnect [10]. To generate optical SSB signal, the EML needs to be operated or configured differently from its typical application as an intensity modulator. Here we introduce three feasible solutions, namely the double-sided EML (DS-EML), the two-segment EML (TS-EML), and the dually modulated EML (D-EML). Fig. 1 illustrates their configurations.

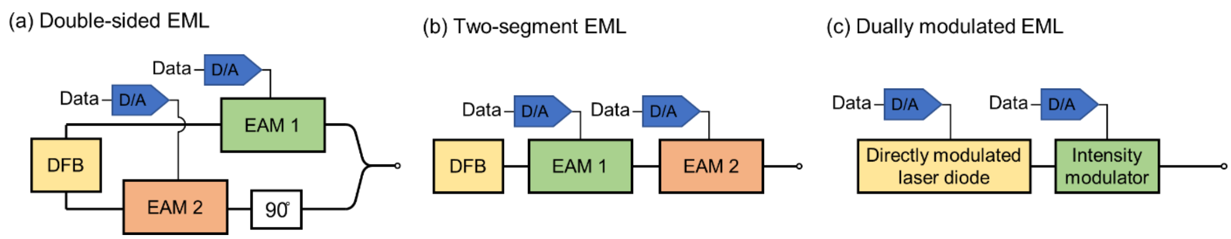

Fig. 1 Three configurations of the EML-based optical SSB transmitter: (a) DS-EML, (b) TS-EML, and (c) D-EML. DFB: distributed feedback laser; D/A: digital-to-analog converter.

DS-EML: The DS-EML integrates two EAM sections at both sides of a DFB section. The light emitted from the DFB can be modulated independently. This design decreases the size and cost of a multi-lane transmitter with the paralleled fibers. It has been fabricated on both InP [11] and Si [12] substrate. Since the light comes from the same laser, it is available to achieve in-phase/quadrature (IQ) multiplexing inside/outside of the DS-EML by introducing a 90-degree phase difference in one EAM branch. In this way, it is feasible to be used as optical SSB transmitter. A prototype is described in [13]. Compared with the optical SSB transmitter based on IQ modulator, the DS-EML scheme suffers from relatively high CSPR and nonlinear transfer curve of the EAM.

TS-EML: The concept of TS-EML comes from the two-segment EAM as reported in [14], in which the optical SSB signal is generated by utilizing the unequal frequency chirp characteristics of the two cascaded EAMs to suppress the unwanted sideband. The chirp of EAM imposes phase/frequency modulation accompanied with the intensity modulation to the optical signal, and it can be tuned by altering the EAM's bias. By setting the two EAMs with different chirp values and pre-distort the frequency-dependent phase of each subcarrier, it is possible to suppress the signal in one sideband while maintain the other. However, the TS-EML suffers from large insertion loss and the cross-beating distortions due to the cascaded EAMs.

D-EML: The dual modulation of EML for the generation of optical SSB signal is first proposed by [15]. This D-EML scheme assumes that the directly modulated laser (DML) serves as a phase modulator through its strong chirp effect while the EAM serves as an intensity modulator, thus any optical field can be synthesized theoretically. A model was developed under this assumption to clarify the amplitude and phase relation (SSB condition) between the driving signals to the laser and modulator section [15]. D-EML exhibits good performance in the narrowband radio-over-fiber applications [16]. The first monolithically integrated D-EML was demonstrated with an overall 3-dB modulation bandwidth of 12 GHz [17].

However, this model encounters problems when generating broadband signals. This is because either the DML or the EAM is not a pure phase or intensity modulator, i.e. the previous model is rather ideal. Later investigation considers the residual intensity modulation of the DML, but not covering the EAM's chirp [18]. To fulfill this gap, we develop a time-harmonic model of dual modulation scheme which includes all the intensity and phase modulation within the DML and EAM [19] and give a closed-form expression for the driving signals. Larger than 40-dB OSSR was achieved with this new model. This is >25 dB higher than the ratios obtained previously.

Further, a broadband-signal model is developed from the time-harmonic model, which assures each frequency component of the signal satisfying the SSB condition over broad frequency range [20]. To achieve this, a digital filter whose frequency response is obtained from the broadband signal model is applied to the signal to be modulated. Meanwhile, the frequency response of the components as well as the length difference in the signal path of the DML and EAM should be compensated digitally. Eventually, a 30-GHz optical SSB signal and 120-Gb/s transmission over 80 km standard single mode fiber was achieved [20]. Later, the channel capacity was improved to 147-Gb/s with the same D-EML transmitter by utilizing discrete multi-tone signal and optical offset filtering [21].

The D-EML utilizes the chirp of the laser (both transient and adiabatic) rather than only employing the EAM's chirp as in TS-EML. The laser's chirp effect is much stronger than the EAM's, especially at the low frequency region. But, the frequency-dependent adiabatic chirp of laser makes the characterization and digital compensation more complicated. Nevertheless, the D-EML makes little modification on the commercial EMLs except giving the ability of direct modulation of laser section. Therefore, it has smaller insertion loss and can benefit from mature fabrication of EML.

3. Conclusions

We review the recent research progress of monolithically integrable optical SSB transmitters and address some crucial merits and demerits of these schemes. The challenges ahead for further performance improvement include mitigation of the nonlinear distortions caused by the on-chip component crosstalk and the EAM's nonlinear transfer curve, more accurate model of the transmitter, and optimization for increasing the output power. Nevertheless, a compact and high-performance optical SSB transmitter would make the optical SSB technology a promising candidate for inter-DC interconnects.

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3. References

[1] X. Zhou, R. Urata, and H. Liu, "Beyond 1 Tb/s intra-data center interconnect technology: IM-DD or coherent?" J. Lightw. Technol. **38**(2), 475–484 (2020).

[2] K. Zhong, X. Zhou, J. Huo, C. Yu, C. Lu, and A. P. T. Lau, "Digital signal processing for short-reach optical communications: a review of current technologies and future trends," J. Lightw. Technol. **36**(2), 377–400 (2018).

[3] R. A. Griffin *et al.*, "10 Gb/s optical differential quadrature phase shift key (DQPSK) transmission using GaAs/AlGaAs integration," in *OFC 2002*, paper FD6.

[4] G. E. Hoefler *et al.*, "Foundry development of system-on-chip InP-based photonic integrated circuits," IEEE J. Select. Topics Quantum Electron. **25**(5), 1–17 (2019).

[5] M. S. Erkılınc *et al.*, "Spectrally-efficient single sideband 16-QAM Nyquist-subcarrier modulation-based WDM transmission using an InP dual-drive Mach-Zehnder modulator and direct-detection," in *ECOC 2015*, paper P.5.1.

[6] T. Zuo, S. Zhang, L. Liu, W. Cheng, and X. Xu, "Single-lane 100Gb/s 4-PAM transmission over 80km SSMF based on K-K scheme and integrated 10G TOSA," in *OFC 2018*, paper Tu2D.6.

[7] Y. Zhang *et al.*, "Experimental demonstration of single sideband modulation utilizing monolithic integrated injection locked DFB laser," J. Lightwave Technol. **38**(7), 1809–1816 (2020).

[8] Y. Zhang *et al.*, "Modulation properties enhancement in a monolithic integrated two-section DFB laser utilizing side-mode injection locking method," Opt. Express **25**(22), 27595 (2017).

[9] Y. Kawamura, K. Wakita, Y. Itaya, Y. Yoshikuni, and H. Asahi, "Monolithic integration of InGaAs/InP DFB lasers and InGaAs/InAlAs MQW optical modulators," Electron. Lett. **22**(5), 242 (1986).

[10] X. Pang *et al.*, "200 Gbps/lane IM/DD technologies for short reach optical interconnects," J. Lightwave Technol. **38**(2), 492–503 (2020).

[11] M. Theurer *et al.*, "2 × 56 GB/s from a double side electroabsorption modulated DFB laser and application in novel optical PAM4 Generation," J. Lightwave Technol. **35**(4), 706–710 (2017).

[12] A. Abbasi *et al.*, "III–V-on-Silicon C-Band high-speed electro-absorption-modulated DFB laser," J. Lightwave Technol. **36**(2), 252–257 (2018).

[13] Y. Yang, D. Lu, J. Gao, M. He, J. Huo, X. Zhou, and K. Long, "Single-sideband (SSB) transmission with a quasi-linear modulator based on double-side electro-absorption modulated laser (DS-EML)," in *ACP 2019,* Paper M4A.115.

[14] H.-L. Cheng, W.-H. Chen, C.-C. Wei, and Y.-J. Chiu, "Optical single-sideband OFDM transmission based on a two-segment EAM," Opt. Express, **23**(2), 982–990 (2015).

[15] H. Kim, "EML-based optical single sideband transmitter," IEEE Photon. Technol. Lett. **20**(4), 243–245 (2008).

[16] J. Petit *et al.*, "Dual modulation of a novel electro-absorption modulated laser for radio-over-fiber systems," Proc. SPIE, (2010).

[17] D. Erasme *et al*., "The dual-electroabsorption modulated laser, a flexible solution for amplified and dispersion uncompensated networks over standard fiber," J. Lightw. Technol. **32**(21), 4068–4078 (2014).

[18] M. E. Chaibi, L. Bramerie, D. Erasme, and C. Peucheret, "Dispersion-Uncompensated Transmission of NRZ and PAM-4 Single-Sideband Signals using D-EML," in *OFC 2018*, paper Tu2C.3.

[19] T. Bo and H. Kim, "Generalized model of optical single sideband generation using dual modulation of DML and EAM," Opt. Express **28**(19), 28491–28501 (2020).

[20] T. Bo, B. Kim, Y. Yu, D. Kim, and H. Kim, "Generation of broadband optical SSB signal using dual modulation of DML and EAM," Journal of Lightwave Technology **39**(10), 3064–3071 (2021).

[21] T. Bo and H. Kim, "147-Gb/s transmission of optical single sideband DMT sgnal generated by dual modulation of DML and EAM," in *OFC 2021*, paper F2D.2.