Short-Reach Transmission Systems

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Short-reach transmission systems are very sensitive to component cost because these systems are often used in a data center, enabling data exchange between many servers and racks.

short-reach transmission link direct detection coherent detection Kramers-Kronig receiver Stokes vector receiver monolithic integrated components

1. Introduction

In recent years, with the applications of various multimedia and data services (e.g., Internet of Things, cloud computing, remote surgery, the construction of 5G, and beyond 5G networks), global network traffic has presented explosive growth over the past decade [1]. Since massive data needs to be stored, transmitted, and processed in a data center, the corresponding traffic also grows rapidly. As the intra- and inter-data center optical interconnects in data center application scenarios [2] require a large number of transmitter and receiver components between servers and racks, the component cost plays a critical role in optical interconnects [3].

Even though the coherent solution with IQ modulation and coherent detection beyond 100-Gbit/s is relatively mature, its transmitter and receiver components with high cost and large footprint size cannot be directly transplanted to short-reach transmission systems. Considering the cost and footprint size, 100-Gbit/s short-reach transmission systems prefer intensity modulation and direct detection (IM/DD) technology [4]. In recent years, numerous 100-Gbit/s IM/DD-based solutions with different transmitter and receiver components have been demonstrated. In these solutions, the transmitter components mainly are vertical-cavity surface-emitting laser (VCSEL) [5][6][7], directly modulated laser (DML) [8][9], Mach-Zehnder modulator (MZM) [10][11], integrated electro-absorption modulated laser (EML) [12][13][14], and monolithic integrated transmitter [15][16]. The receiver components usually contain single-end photodetector (PD), Kramers-Kronig receiver [17][18], Stokes vector receiver [19][20][21], and monolithic integrated receiver [22][23]. Here, it is commonly considered that monolithic integrated transmitter and receiver under low-cost and small footprint size have great potential to be the candidate transmitter and receiver component for next-generation high-speed short-reach transmission systems.

In order to further increase the transmission capacity of IM/DD systems, advanced multi-level modulation formats, polarization division multiplexing, and powerful digital signal processing algorithms have been introduced to support high-speed short-reach transmission systems [24]. However, when a lane rate increases from 100-Gbit/s to 400-Gbit/s, a smooth transition from the IM/DD technology to digital coherent technology will be in progress; of course, there are still many challenges. The conventional transmitter and receiver components in digital coherent technology are not cost-effective [25], so that these components cannot be directly transplanted to short-reach transmission systems. In addition to the digital coherent technology and the traditional IM/DD technology, some advanced direct detection technologies such as Kramers-Kronig receiver [17][18] and Stokes vector receiver [19][20][21] have been proposed and studied extensively. Since these techniques can reconstruct the complex domain of the signal, rate-distance product can be further improved by combing impairments compensation algorithms and advanced modulation technology. These advanced techniques can be treated as a compromise between the digital coherent technology and the traditional IM/DD technology. Recently, an effective solution, a transceiver integration scheme based on the digital coherent technology [26][27], has been reported and shows the potential to reduce cost and footprint size of the transmitter and receiver components dramatically. Subsequently, the transceiver integration scheme for multiple parallel IM/DD channels [28] has also been demonstrated.

2. Integrated Components and Solutions for High-Speed Short-Reach Data Transmission

It is well-known that short-reach transmission systems are extremely sensitive to cost of components due to the enormous scale of deployments in intra- and inter-data center optical interconnects. Thus, optical transmitters and receivers at low-cost are required in these applications. To select cost-effective transmitter and receiver components more equitably, the technology and component options based on different transmission distances have been summarized in Figure 1. Note that the cost of components usually includes material cost, yield rate, packaging cost, test cost, design cost, and so on. Most of these costs are difficult to predict in the actual production process, thus it is hard to calculate the accurate cost of components. Here, the relative costs of various components are discussed.

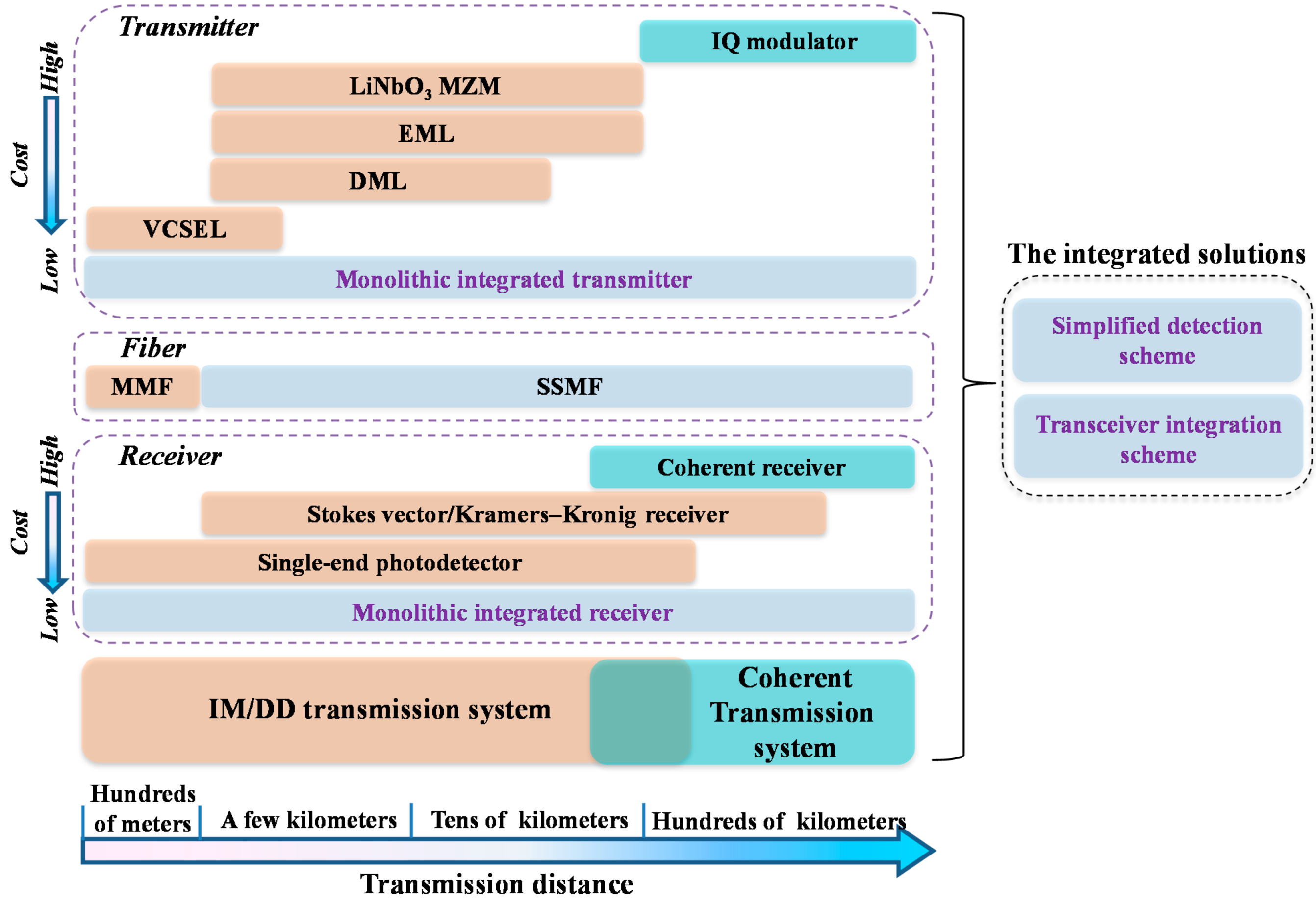

Figure 1. The technological and component options for high-speed short-reach transmission systems.

With the development of low-cost coherent detection and monolithic integration technologies, VCSEL, DML, EML, MZM, IQ modulator, and monolithic integrated transmitter have been the major options to construct the transmitter of high-speed short-reach transmission systems. Here, we compare the supported wavelength λ, supported fiber type, transmission distance, bandwidth, frequency chirp, footprint, and relative cost of different transmitter components as depicted in Table 1. The transmission signal in C-band would be greatly affected by CD effect. In IM/DD transmission systems, since the transmission signal is often a double sideband, the interaction between square law detection in single-end PD and CD would produce fiber power fading, which may cause severe ISI contributions to their adjacent symbols. In addition, since the electrical signals of direct modulation components such as VCSEL and DML are directly applied to their laser cavities, these components whose responses were caused by transient chirp and adiabatic chirp would show a higher frequency chirp than EML caused by transient chirp. While, for external modulation components such as MZM, IQ modulator and monolithic integrated transmitter, the frequency chirp does not exist. The interplay between the frequency chirp and CD would induce severe nonlinear distortions and lead to serious degradation of transmission performance. To deal with these problems, DML is applied in mostly <40-km O-band high-speed transmission systems. In addition, the application of VCSEL is mostly used in hundreds of meters of 850-nm few-/multi-mode transmission systems so that the influence of CD can be weakened to a certain extent. It is generally believed that the combination of MM-VCSEL and MMF has been recognized as a highly effective solution for <300-m short-reach optical interconnects.

Certainly, the SM-VCSEL combining MMF or SMF system can support a few kilometers transmission distance. On the other hand, the bandwidth is another important factor in the selection of transmitter components. The bandwidth of monolithic integrated transmitter is usually greater than 40-GHz. Generally, despite many efforts made to achieve beyond 100-Gbit/s per lane signal transmission, the common bandwidth of VCSEL is around 25-GHz, while that of DML is less than 30-GHz. To break the DML bandwidth ceiling of around 30 GHz, special physical effects including detuned-loading and photon-photon resonance have been introduced to enhance the laser response in the high frequency region, and the state-of-art bandwidth of DML can be up to 100-GHz [29]. The common bandwidths of MZM and EML are beyond 30-GHz in beyond 100-Gbit/s per lane transmission systems, although the state-of-art bandwidth 100-GHz of EML had been reported [13]. In general, for hundreds of meters of high-speed intra-data center optical interconnects, VCSEL with low-cost and small footprint size is commonly considered as the best candidate transmitter. For a few and tens of kilometers high-speed optical interconnects, the best choice becomes unobvious between DML and EML. Of course, in terms of cost, a few kilometers high-speed optical interconnects prefer to use DML. In here, for the cost-sensitive short-reach transmission systems, $LiNbO_3$-based MZM and IQ modulator with large footprint size and high-cost may not be the best transmitter option. Currently, with the help of monolithic integration technology, the MZM and IQ modulator-based monolithic integrated transmitters based on InP-based monolithic integration or SiP have shown irreplaceable advantages in cost, package, bandwidth, and transmission distance compared with other transmitters. Therefore, we believe that the monolithic integrated transmitters have the potential to gradually replace other transmitters in high-speed short-reach transmission systems in the future, especially in tens of kilometers of high-speed optical interconnects.

Table 1. Comparison of different transmitters applied in beyond 100-Gbit/s per lane data transmission.

Tx	λ	Fiber	Reach	BW	Chirp	Footprint	Cost
IQ Modulator	O-/C-Band	SMF	>80 km	high	--	high	high
MZM	O-/C-Band	SMF	<80 km	high	--	high	high
EML	O-/C-Band	SMF	<80 km	high	low	moderate	moderate
DML	Mostly O-Band Partially C-Band	SMF	<40 km	moderate	high	low	low
VCSEL	Mostly 850 nm Partially C-Band	MMF/SMF	<300 m <2 km	low	high	low	Very low
Monolithic integrated transmitter	O-/C-Band	SMF	whole range	high	--	low	moderate

In recent years, various receivers such as single-end PD, Kramers-Kronig receiver, Stokes vector receiver, coherent receiver, and monolithic integrated receiver have been widely reported in beyond 100-Gbit/s short-reach transmission systems. Here, as depicted in Table 2, we compare the supported transmission distance, detection sensitivity, footprint, and cost of different receiver components in beyond 100-Gbit/s per lane transmission system. For the IM/DD transmission system, beyond 100-Gbit/s researches mainly use the single-end PD with low-cost to detect the transmission signals. The single-end PD can only detect intensity information, and its applications are often limited to less than tens of kilometers of transmission distance because CD effect would lead to serious inter-symbol interference. While, this phenomenon may be even worse for high-speed transmission links as these links can be more sensitive to signal impairments. Many advanced direct detection technologies such as Kramers-Kronig receiver and Stokes vector receiver have been proposed and studied extensively, and the gap between conventional direct detection and advanced coherent detection is getting closer. Since these techniques can reconstruct the complex domain of the modulation signal, the CD effect can be compensated in the DSP module of receiver side. Meanwhile, to combine complex vector modulation with polarization division multiplexing, the rate-distance product can be further improved. Despite these advanced direct detection technologies having large footprint size and moderate cost compared to a single-end PD, they still show the potential in certain application scenarios. Coherent receiver with high detection sensitivity has the ability to achieve high rate-distance product, but its cost is too high to use directly in cost-sensitive short-reach transmission systems. In recent years, InP/SiP-based monolithic integrated receivers incorporating various schemes, such as single-end PD, Kramers-Kronig receiver, Stokes vector receiver, and coherent receiver have been widely reported and have the advantages of low-cost and small footprint size. Furthermore, some effective solutions combining simplified direct scheme and transceiver integration scheme have also been reported in short-reach transmission systems for the purpose of cost and energy effectiveness.

Table 2. Comparison of different receiver components applied in beyond 100-Gbit/s per lane data transmission.

Rx	Reach	Footprint	Sensitivity	Cost
Coherent receiver	high	high	high	high
Stokes vector receiver	moderate	moderate	moderate	moderate
Kramers-Kronig receiver	moderate	moderate	moderate	moderate
Single-end PD	low	low	low	low
Monolithic integrated receiver	whole range	low	whole range	Very low

References

1. Al-Turjman, F.; Ever, E.; Zahmatkesh, H. Small Cells in the Forthcoming 5G/IoT: Traffic Modelling and Deployment Overview. IEEE Comm. Surv. Tutor. 2019, 21, 28–65.
2. Kachris, C.; Kanonakis, K.; Tomkos, I. Optical interconnection networks in data centers: Recent trends and future challenges. IEEE Commun. Mag. 2013, 51, 39–45.
3. Briscoe, B.; Brunstrom, A.; Petlund, A.; Hayes, D.; Ros, D.; Tsang, J.; Gjessing, S.; Fairhurst, G.; Welzl, M. Reducing internet latency: A survey of techniques and their merits. IEEE Comm. Surv. Tutor. 2014, 18, 2149–2196.
4. Eiselt, M.H.; Eiselt, N.; Dochhan, A. Direct Detection Solutions for 100G and Beyond. In Proceedings of the Optical Fiber Communication Conference, Los Angeles, CA, USA, 19–23 March 2017; p. Tu3I.3.
5. Ledentsov, N.N.; Shchukin, V.A.; Kalosha, V.P.; Ledentsov, N., Jr.; Chorchos, L.; Turkiewicz, J.P.; Hecht, U.; Kurth, P.; Gerfers, F.; Lavrencik, J.; et al. Optical Interconnects Using Single-Mode and Multi-Mode VCSEL and Multi-Mode Fiber. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 8–12 March 2020; p. M3D.1.
6. Zuo, T.; Zhang, L.; Zhou, J.; Zhang, Q.; Zhou, E.; Liu, G.N. Single Lane 150-Gb/s, 100-Gb/s and 70-Gb/s 4-PAM Transmission over 100-m, 300-m and 500-m MMF Using 25-G Class 850nm VCSEL. In Proceedings of the European Conference on Optical Communication, Dusseldorf, Germany, 18–22 September 2016; pp. 1–3.
7. Tatum, J.A.; Landry, G.D.; Gazula, D.; Wade, J.K.; Westbergh, P. VCSEL-Based Optical Transceivers for Future Data Center Applications. In Proceedings of the Optical Fiber Communication Conference and Exhibition, San Diego, CA, USA, 11–15 March 2018; p. M3F.6.
8. Wang, W.; Zhao, P.; Zhang, Z.; Li, H.; Zang, D.; Zhu, N.; Lu, Y. First Demonstration of 112 Gb/s PAM-4 Amplifier-free Transmission over a Record Reach of 40 km Using 1.3 μm Directly Modulated Laser. In Proceedings of the Optical Fiber Communication Conference Postdeadline Papers, San Diego, CA, USA, 11–15 March 2018; p. Th4B.8.
9. Xu, Z.; Sun, C.; Ji, T.; Ji, H.; Shieh, W. Cascade Recurrent Neural Network Enabled 100-Gb/s PAM4 Short-Reach Optical Link Based on DML. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 8–12 March 2020; p. W2A.45.
10. Wei, Y.; Yu, J.; Shi, J.; Zhang, J.; He, J.; Chen, L. Demonstration of C-band 112G PAM-4 transmission over 80-km stand-single mode fiber based on direct-detection. Opt. Commun. 2018, 424, 32–36.
11. Estaran, J.; Rios-Mueller, R.; Mestre, M.A.; Jorge, F.; Mardoyan, H.; Konczykowska, A.; Dupuy, J.-Y.; Bigo, S. Artificial Neural Networks for Linear and Non-Linear Impairment Mitigation in High-Baudrate IM/DD Systems. In Proceedings of the European Conference on Optical Communication, Dusseldorf, Germany, 18–22 September 2016; pp. 1–3.

12. Nada, M.; Yoshimatsu, T.; Muramoto, Y.; Ohno, T.; Nakajima, F.; Matsuzaki, H. 106-Gbit/s PAM4 40-km Transmission Using an Avalanche Photodiode with 42-GHz Bandwidth. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 11–15 March 2018; p. W4D.2.
13. Chaciński, M.; Westergren, U.; Stoltz, B.; Thylén, L.; Schatz, R.; Hammerfeldt, S. Monolithically Integrated 100 GHz DFB-TWEAM. IEEE J. Lightwave Technol. 2009, 27, 3410–3415.
14. Chan, T.K.; Way, W.I. 112 Gb/s PAM4 transmission over 40km SSMF using 1.3 µm gain-clamped semiconductor optical amplifier. In Proceedings of the Optical Fiber Communication Conference, Los Angeles, CA, USA, 22–26 March 2015; p. TH3A.4.
15. Lange, S.; Wolf, S.; Lutz, J.; Altenhain, L.; Schmid, R.; Kaiser, R.; Koos, C.; Randel, S.; Schell, M. 100 GBd Intensity Modulation and Direct Detection with an InP-based Monolithic DFB Laser Mach-Zehnder Modulator. In Proceedings of the Optical Fiber Communication Conference Postdeadline Papers, Los Angeles, CA, USA, 19–23 March 2017; p. Th5C.5.
16. Yamazaki, H.; Nagatani, M.; Wakita, H.; Ogiso, Y.; Nakamura, M.; Ida, M.; Nosaka, H.; Hashimoto, T.; Miyamoto, Y. IMDD transmission at net data rate of 333 Gb/s using over-100-GHz-bandwidth analog multiplexer and Mach–Zehnder modulator. IEEE J. Lightwave Technol. 2019, 37, 1772–1778.
17. Li, Z.; Erkılınç, M.S.; Shi, K.; Sillekens, E.; Galdino, L.; Thomsen, B.C.; Bayvel, P.; Killey, R.I. SSBI Mitigation and the Kramers-Kronig Scheme in Single-Sideband Direct-Detection Transmission With Receiver-Based Electronic Dispersion Compensation. IEEE J. Lightwave Technol. 2017, 35, 1887–1893.
18. Mecozzi, A.; Antonelli, C.; Shtaif, M. Kramers-Kronig coherent receiver. Optica 2016, 3, 1220–1227.
19. Chagnon, M.; Osman, M.; Patel, D.; Veerasubramanian, V.; Samani, A.; Plant, D. 1λ 6 bits/symbol 280 and 350 Gb/s direct detection transceiver using intensity modulation polarization multiplexing and inter-polarization phase modulation. In Proceedings of the Optical Fiber Communication Conference Postdeadline Papers, Los Angeles, CA, USA, 22–26 March 2015; p. Th5B.2.
20. Che, D.; Li, A.; Chen, X.; Hu, Q.; Wang, Y.; Shieh, W. Stokes vector direct detection for linear complex optical channels. IEEE J. Lightwave Technol. 2015, 33, 678–684.
21. Kikuchi, K. Electronic polarization-division demultiplexing based on digital signal processing in intensity-modulation direct-detection optical communication systems. Opt. Express 2014, 22, 1971–1980.
22. Ding, Y.; Cheng, Z.; Zhu, X.; Yvind, K.; Dong, J.; Galili, M.; Hu, H.; Mortensen, N.A.; Xiao, S.; Oxenløwe, L.K. Ultra-compact integrated graphene plasmonic photodetector with bandwidth above 110 GHz. Nanophotonics 2019.

23. Ghosh, S.; Kawabata, Y.; Tanemura, T.; Nakano, Y. Polarization-analyzing circuit on InP for integrated Stokes vector receiver. Opt. Express 2017, 25, 12303–12310.
24. Pang, X.; Ozolins, O.; Lin, R.; Zhang, L.; Udalcovs, A.; Xue, L.; Schatz, R.; Westergren, U.U.; Xiao, S.; Hu, W.; et al. 200 Gbps/Lane IM/DD Technologies for Short Reach Optical Interconnects. IEEE J. Lightwave Technol. 2020, 38, 492–503.
25. Cheng, Q.; Bahadori, M.; Glick, M.; Rumley, S.; Bergman, K. Recent advances in optical technologies for data centers: A review. Optica 2018, 5, 1354–1370.
26. Doerr, C.; Chen, L.; Vermeulen, D.; Nielsen, T.; Azemati, S.; Stulz, S.; McBrien, G.; Xu, X.; Mikkelsen, B.; Givehchi, M.; et al. Single-Chip Silicon Photonics 100-Gb/s Coherent Transceiver. In Proceedings of the Optical Fiber Communication Conference Postdeadline Papers, San Francisco, CA, USA, 9–13 March 2014; p. Th5C.1.
27. Lal, V.; Studenkov, P.; Frost, T.; Tsai, H.; Behnia, B.; Osenbach, J.; Wolf, S.; Going, R.; Porto, S.; Maher, R.; et al. 1.6Tbps Coherent 2-Channel Transceiver Using a Monolithic Tx/Rx InP PIC and Single SiGe ASIC. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 8–12 March 2020; p. M3A.2.
28. Aoki, T.; Sekiguchi, S.; Simoyama, T.; Tanaka, S.; Nishizawa, M.; Hatori, N.; Sobu, Y.; Sugama, A.T.; Akiyama, H.A.; Muranaka, H.; et al. Low-Crosstalk Simultaneous 16-Channel × 25 Gb/s Operation of High-Density Silicon Photonics Optical Transceiver. IEEE J. Lightwave Technol. 2018, 36, 1262–1267.
29. Yamaoka, S.; Diamantopoulos, N.; Nishi, H.; Nakao, R.; Fujii, T.; Takeda, K.; Hiraki, T.; Kanazawa, S.; Tanobe, H.; Kakitsuka, T. 239.3-Gbit/s net rate PAM-4 transmission using directly modulated membrane lasers on high-thermal-conductivity Sic. In Proceedings of the European Conference on Optical Communication, Dublin, Ireland, 22–26 September 2019; pp. 1–4.