Coupled Waveguides for Optical Multiplexing in High-Performance Interconnects

Yoav Shechtman[1], Bhavin J. Shastri[2], Ben Wu[2], Paul R. Prucnal[2], and Mordechai Segev[1]
[1]Physics Department, Technion – Israel Institute of Technology, Haifa, Israel
[2]Lightwave Communications Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA
joe@tx.technion.ac.il

Abstract: We propose and demonstrate a proof-of-concept for a novel multiplexing scheme for high-performance optical interconnects. Our approach is based on waveguide coupling using multilevel detection to increase the system throughput without increasing aggregate bit rate.

OCIS codes: (200.4650) Optical interconnects; (230.7370) Waveguides

1. Introduction

The coming decade is expected to witness high-end computing systems—supercomputers and data centers—scale from petascale to exascale [1]. The physics (bandwidth–length product, electromagnetic interference and propagation losses) of copper wire interconnects will not be able to grow to meet this demand. These systems will require an entirely new approach to interconnect architectures and implementations, namely, optical interconnects in order to meet bandwidth and power efficiency requirements with high levels of integration in a cost-effective manner [2]. Consequently, to realize this, some form of multiplexing scheme will be required for both intra-chip and on-chip communications [3]. Time division multiplexing (TDM) [4] faces various scalability challenges as the aggregate bit rate cannot be scaled arbitrarily high with physical impairment limitations. Wavelength division multiplexing (WDM) [5] overcomes the limitations of TDM; however, it is associated with cost, design complexity, and high precision necessity of the system.

Here, we propose and demonstrate an experimental proof of concept of a novel multiplexing method using coupled waveguides that results in an *M*-level pulse-amplitude modulation (PAM-*M*). PAM-*M* signaling has the ability to mitigate frequency-dependent attenuation and fiber dispersion, and thus lower the link budget, with PAM-4 achieving better link performance than on-off keying modulation [6]. Vertical-cavity surface-emitting lasers (VCSELs) have been explored as an alternative approach to achieve higher speed digital modulation [7]. However, the complexity of the design and implementation of VCSEL driver circuits prevents a widespread system-level evaluation. Our all-optical scheme allows for increase in the spectra efficiency, system throughput and hence the capacity without increasing the aggregate electronic bit rate. This approach reduces the cost, power consumption, and space with a single receiver employing a multilevel detection scheme. Furthermore, our scheme can utilize a broad-band light source, relaxing the stringent design requirements of a WDM system.

2. Coupled waveguides

The basic building block of the proposed communication system is a pair of adjacent identical single-mode waveguides. The waveguides are closely spaced and they are designed so that the coupling between them is non-negligible. Inputting light into two closely spaced identical waveguides results in energy oscillations between their eigenmodes [8], according to: $P_a(z) = P_0 \sin^2(kz)$, $P_b(z) = P_0 - P_a(z)$, with P_a and P_b being the eigenmode power in waveguides a and b respectively, as a function of propagation distance z, and k being a function of their separation, depth and refractive indices [8]. Detecting the power at the exit of the waveguides after a propagation distance of z_0, yields an x: $(1-x)$ coupler, with $x < 1$. Specifically, we shall focus on the case $x = 1/3$.

Using a binary input, that is, either 0 or 1 in both waveguides, there are four input possibilities, or 2 bits. By performing multilevel power measurement, the exit power of only one waveguide, say waveguide a, the 2-bit input may be recovered. This is because each possible 2-bit input corresponds uniquely to a different output power in the measured waveguide. For example, the input condition $P_a(z=0) = 0$, $P_b(z=0) = 1$, leads to the measured power of $1/3$. Similarly, the other input conditions: 0–0, 1–0, 1–1 would yield measured output power of $0, 2/3, 1$, respectively, hence setting multi-detection thresholds at $1/6, 3/6, 5/6$ yields unique output-input relations. In the above analysis, an incoherent sum of the waveguides' modes is assumed. Such would be the case if the light sources are broad-band (e.g. LED), or if the inputs into the two waveguides are of sufficiently spaced wavelengths.

For our application, we aim to employ silicon (Si)-wire waveguides as they are attractive structures to use for optical interconnections on Si chips for high-density integration [1]. First, we simulate two Si-wire waveguides with 0.3 μm × 0.3 μm cross-sections that are 0.1 μm apart, in the geometry presented in [9], using three-dimensional finite element method (FEM). The numerical simulation agrees with the coupled-waveguide theory, and indicates that the silicon wire geometry presented in [9] is suitable for the multi-level directional coupler application.

3. Experimental setup, results, and analysis

The concept is verified by the experimental setup shown in Fig. 1(a). The two coupled waveguides are emulated by two fibers coupled by a fiber coupler with a tunable coupling ratio selected as 67:33. The inputs to the coupler, *a* and *b*, are generated by modulating two independent distributed feedback (DFB) lasers with outputs from a pattern generator by driving their respective polarization-dependent Mach–Zehnder modulators (MZMs). The input signals to be multiplexed at the coupler are 2^{15}–1 pseudorandom binary sequence patterns at 10 Gb/s. The four-level output signal is then demultiplexed at the receiver by a 2-bit flash analog-to-digital converter into two bits before being sent to a bit error rate tester (BERT). The 10 Gb/s multiplexed four-level eye-diagram of the coupler's output [at (iii)] is shown in Fig.1(b); the demultiplexed two-level eye diagram after the receiver [at (iv), one of the BERT inputs] is shown in Fig.1(c). The measured BER versus receiver power is shown in Fig. 2(a), for different data-rates.

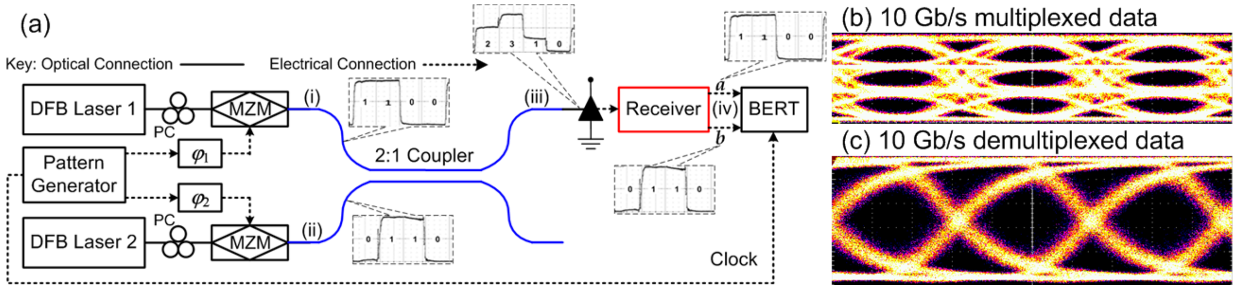

Fig. 1. (a) Experimental setup. Eye diagrams of 10 Gb/s (b) multiplexed [at (iii) after coupler] and (c) demultiplexed data [at (iv) after receiver].

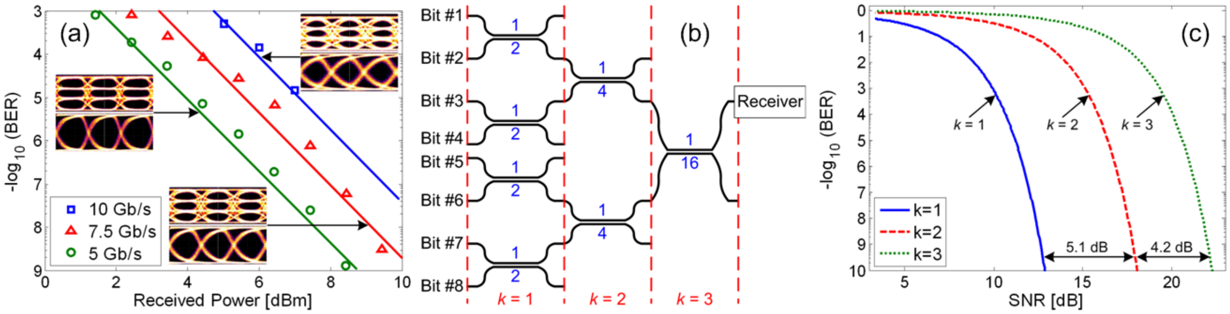

Fig. 2. (a) Experimentally measured BER versus receiver power for different data rates (insets: eye diagrams of multiplexed and demultiplexed data). (b) 8-bit coupled system (the numbers near the couplers' arms represent the coupling ratios). (c) BER versus SNR for different serialization levels (simulation).

The above idea can be extended using the two-waveguides as a building block. As illustrated in Fig. 2(b), 8 bits are uniquely mapped into a single output with three levels of serialization. The limit on the system's scalability comes from noise. To study these limitations, we theoretically derive the BER performance of the coupled waveguides as a function of signal-to-noise ratio (SNR) for different levels of serialization as shown in Fig. 3(b).

4. Conclusion

We have proposed and demonstrated an efficient multiplexing method based on waveguide coupling, using multilevel detection. This scheme increases the system's throughput without increasing the aggregate electronic bit rate, and is limited by the SNR, as opposed to switching/detection speed (TDM), or cost/design complexity (WDM).

[1]. R. G. Beausoleil, "Large-scale integrated photonics for high-performance interconnects," ACM J. Emerg. Technol. Comput. Syst., **7**,(2011).
[2]. B. J. Offrein, "Optical interconnects for computing applications," in *Proceedings of IEEE Photonics Conference*, (2012), paper MV.1.
[3]. M. Petracca, K. Bergman, and L. P. Carloni, "Photonic networks-on-chip: opportunities and challenges," in *Proceedings of IEEE International Symposium on Circuits and Systems,* (2008), pp. 2789–2792.
[4]. A. Aboketaf, A. W. Elshaari, and S. F. Preble, "Optical time division multiplexer on silicon chip," *Opt. Express,* **18**, 13529–13535, (2010).
[5]. B. E. Nelson,G. A. Keeler, D. Agarwal, N. C. Helman, D. A. B. Miller, "Wavelength division multiplexed optical interconnect using short pulses," *IEEE. J. Sel. Topics Quantum Electron.*, **9**, 486–491, (2003).
[6]. S. Walkin and J. Conradi, "Multilevel signaling for increasing the reach of 10 Gb/s lightwave systems," *J. Lightw. Technol.*, **17**, 2235–2248, (1999).
[7]. B. J. Shastri, C. Chen, K. D. Choquette, and D. V. Plant, "Circuit modeling of carrier–photon Dynamics in composite-resonator vertical-cavity lasers," *IEEE. J. Quantum Electron.*, **47**, 1537–1546, (2011).
[8]. A. Yariv, *Optical Electronics in Modern Communications,* 5th ed., (Oxford: Oxford U. Press, 1997).
[9]. H. Yamada, T. Chu, S. Ishida, and Y. Arakawa, "Optical directional coupler Based on Si-wire waveguides," *IEEE Photon. Technol. Lett.*, **17**, (2005).