Free-Space Optical Link With Spatial Redundancy for Misalignment Tolerance

E. Bisaillon, D. F. Brosseau, T. Yamamoto, M. Mony, E. Bernier, D. Goodwill, D. V. Plant, and A. G. Kirk

***Abstract*—Free-space optical interconnects can provide high bandwidth with no physical contact, but suffer from poor tolerances to misalignment. In order to obtain high misalignment tolerances, we propose the use of an active alignment scheme in conjunction with an optimized optical design. The active alignment scheme uses a redundant set of optical links and the active selection of the best link. The optical design maximizes the alignment tolerances between the two boards to ± 1 mm of lateral and $\pm 1°$ of angular misalignment for a target data rate of 1.25 Gb/s.**

***Index Terms*—Free space, microlenses, misalignment tolerance, optical interconnect, spatial redundancy, vertical-cavity surface-emitting laser.**

I. Introduction

PARALLEL optical interconnects have the potential to provide high bandwidth communication within computers and switches [1], [2]. The board-to-board interconnection challenge can be approached by using rigid free-space optics, which tend to suffer from stringent alignment requirements, or by the use of fiber image guides or parallel fiber arrays which require connectorization. Free-space interconnects can provide, however, more flexible links, a feature that may be a key benefit for applications. The parallel nature of free-space interconnects can be employed to provide massively parallel optical data links. However, an alternative approach is to exploit the available parallelism in order to increase tolerance to misalignment through the use of spatial redundancy. In this approach, arrays of redundant sources and detectors are used to encode a single channel [1]–[3]. Previous work [3] has explored solutions to this problem using a large area detector. The solution presented here, offers a scalable design with smaller crosstalk between clusters in the event of a parallel implementation, as well as higher data rates due to the reduced area, and thus, capacitance of the photodetectors.

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E. Bisaillon and M. Mony are with AcceLight Networks, Inc., Pittsburgh, PA 15017 USA.

D. F. Brousseau is with The Canadian National Railway Company, Montreal, H3B 2M9 QC, Canada.

T. Yamamoto is with the Photonic Network Switching Research Group, NTT Optical Network Systems Laboratories, 120-002 Kanagawa, Japan.

E. Bernier is with Nortel Networks, ON K1Y 4H7, Canada.

D. Goodwill is with Advanced Design Technology-Nortel Networks, Kanata, ON K1Y 4H7, Canada.

D. V. Plant and A. G. Kirk are with the Department of Electrical and Computer Engineering, McGill University, Montréal. QC H3A 4H7, Canada.

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The use of spatial redundancy, i.e., the selection of redundant source-detector array pairs alone, cannot necessarily guarantee the adequate performance of the system under all cases of lateral and angular misalignment. The need arises for this redundancy to be accompanied by an optimized optical design that guarantees an efficient source-detector power coupling in the desired misalignment tolerance window. In Section II, we present a novel optical design which achieves this objective based on the use of arrays of vertical-cavity surface-emitting lasers (VCSELs) and photodetectors (PDs). Section III describes the packaging of the optical link components. The implementation of optical link is presented in Section IV followed by the test and characterization of the performance of the link in Section V. The optical link presented in this letter, is integrated in a double bidirectional free-space interconnect between two printed circuit boards, separated by a distance ranging from 5 to 25 cm, which can sustain a ± 1-mm lateral misalignment, and a $\pm 1°$ angular misalignment between them. These values were selected as reflecting real-world alignment tolerances for board insertion. Some of these components have previously been described in [4]–[6].

II. Optical Design

The optical system was required to provide a maximum power coupling efficiency, between a 3×3 array of single-mode 960-nm 3-μm diameter VCSELs with a 250-μm pitch, and 3×3 array of 70-μm diameter PDs with a 125-μm pitch, under any degree of lateral or angular misalignment within the specified limits. This scalable optical design was achieved using both ray tracing and Gaussian beam propagation algorithms [5]. Each VCSEL in the array emits -2.22 dBm of optical power. The predicted receiver sensitivity at a data rate of 1.25 Gb/s resulted in a requirement of at least -23 dBm of optical power coupled into the PDs. This budget allowed for an optical loss, mainly due to the defocus of the beams at the PD plane of 20 dB. The conservative approach to the optical design was taken in order to allow for a maximum coupling loss of 15 dB. Four of these optical links, comprising four source arrays and four detector arrays form a double bidirectional system. A schematic of system is show in Fig. 1.

The optical link system for the transmitter consisted of a planar microlens (PML) array to collimate the VCSELs and a macrolens to relay the beams. The receiver part of the link uses only macrooptics. A schematic of the optical link is shown in Fig. 2.

The simulations were simplified by considering the symmetry of the source and detector arrays used. This helped in

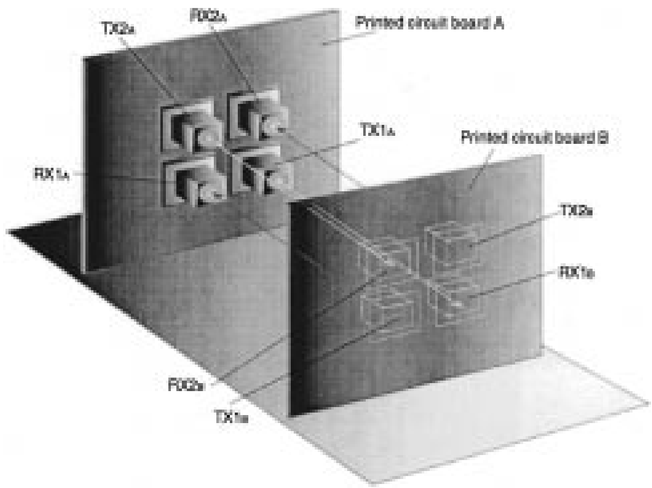


Fig. 1. Double bidirectional optical interconnects between two printed circuit boards.

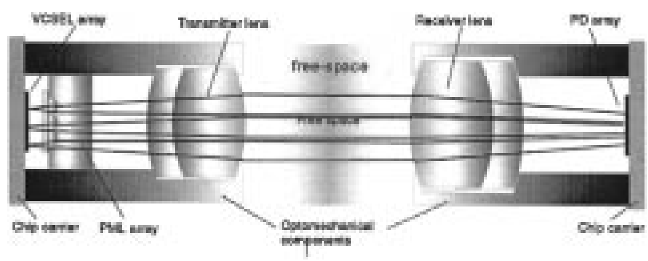


Fig. 2. Optical link for a redundant assembly.

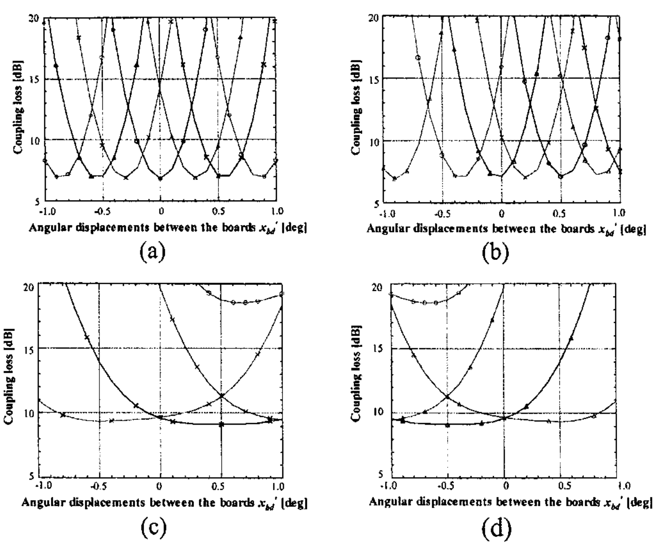


Fig. 3. Optical coupling loss between source and detector for different (shown on the different set of curves) VCSEL-PD pairs, under different misalignment conditions. (a) and (b) are for a 5-cm distance between the boards, with no misalignment and 1-mm misalignment, respectively. (c) and (d) are for a distance of 20 cm between the boards, with a lateral misalignment of 0 and 1 mm, respectively.

reducing the problem to a two-dimensional (2-D) propagation method. The simulated system behavior under maximal and no misalignment conditions is shown in Fig. 3.

The simulations show, that under all cases of lateral and angular misalignments, even under the worse case misalignment [see Fig. 3(d)], there always exists a VCSEL-PD pair that keeps the coupling loss below 15 dB.

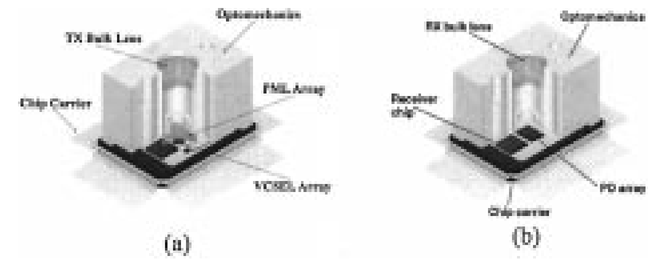


Fig. 4. Transmitter and receiver modules.

III. Packaging

Each optical link was composed of both a transmitter and a receiver module. Both modules were contained in an optomechanical mount attached to a ceramic chip carrier, as shown in Fig. 4.

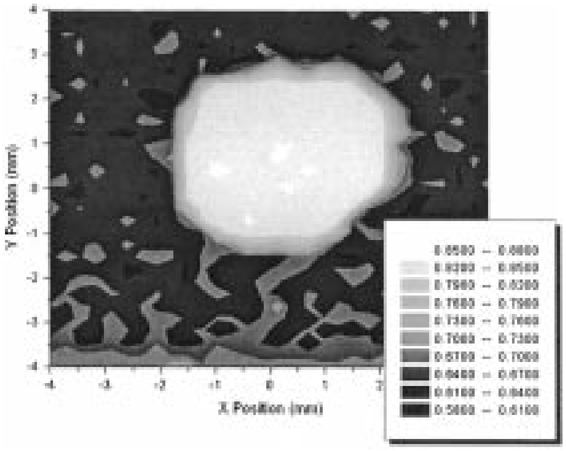
The transmitter module contained the planar microlens array and the bulk 12-mm focal length collimating lens. The receiver module contained only a 15-mm focal length achromatic focusing lens. The packages for the transmitter and receiver components rest on a ceramic electronic chip carrier [4]. In the case of the transmitter optoelectronics, careful attention was paid to the parallelism between the VCSEL array and the PML array. This required custom machining and the use of even bond-line epoxy. All optical components (both macrolenses and PML array) were AR coated for maximum transmission at the working wavelength of 960 nm.

IV. Optical Link Implementation

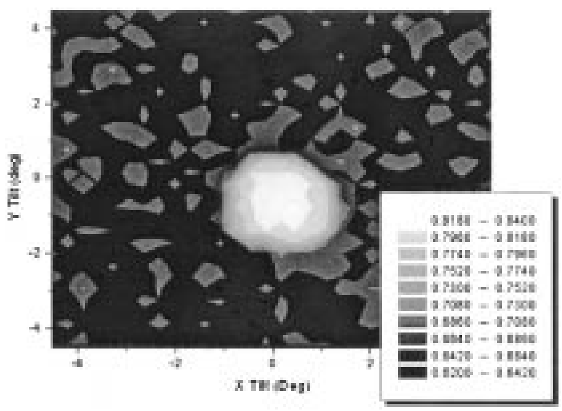
The optical link was implemented using both passive and active alignment techniques. The system is aligned mechanically under no lateral misalignment. When misalignment is introduced, redundancy is used to guarantee proper optical performance. The PML array was glued to the optomechanical mount using machined alignment markers. The achromatic macrolenses were attached by sliding fit insertion into the optomechanical mounts. The alignment of the optics to the electronics, i.e., the alignment of the PML array, lying on the optomechanical mount, to the VCSEL array was the most critical part of the implementation. The printed circuit board holding the optoelectronics was placed on a transverse motion stage and the optical modules mounted on their own holder, which was attached to a six degrees of freedom computer-controlled positioning stage. A combination of active alignment (through the observation of the transmitted VCSEL beam) and passive alignment (through the observation of interference fringes between the VCSEL substrate and the PML array surface generated by an external guide beam) was used. This resulted in an alignment precision of 1 μm laterally and 0.01° angularly [5].

V. System Characterization

Two of the populated boards were then placed on microcontrolled translation stages in order to provide accurate characteri-



(a)



(b)

Fig. 5. (a) The lateral and (b) angular best-case receiver voltage, using the redundancy of the VCSEL-PD pairs.

zation of both the link performance and the misalignment tolerance. Lateral and tilt misalignment tolerance was characterized with the help of an algorithm that selected, out of the possible 81 VCSEL-PD combinations, the best possible pair. Fig. 5 shows the lateral and angular misalignment tolerances of the link.

The tolerance to misalignment was determined by the sensitivity of receiver. The receiver bandwidth, for a bit error rate (BER) of 10^{-12} was determined to range from 18.5 to 750 Mb/s. The maximum sensitivity was obtained at a data rate of 450 Mb/s, and thus, this bitrate was chosen to perform the misalignment tolerance characterization [6]. As can be observed from these graphs, there is a sharp transition from the regime where the receiver functions properly (light gray region) to the regime where only noise is obtained (dark gray region). These results show that the link, with a separation between boards of 20 cm, was tolerant to a 1.2-mm lateral misalignment, as seen in Fig. 5(a).

Fig. 5(b) reveals the 1.1° angular tolerance of the optical link, shown again by the sharp transition. Darker regions inside the observed tolerance region are due to the higher coupling losses occurring for certain misalignment conditions, as expected from the simulations. The measured receiver sensitivity (required to produce a voltage greater than 0.77 V) on Fig. 5 was found to be −11.9 dBm. Although this is significantly less sensitive than the original design target of −23 dBm, the optical loss of the system was also commensurately lower. In the regions of misalignment tolerance shown in Fig. 5, the optical loss was less than 9.7 dB. This suggests that if the target receiver sensitivity had been obtained the misalignment tolerance range would further increase.

VI. Conclusion

The use of a redundant array of sources and detectors represents a novel solution to the misalignment problem in free space optical interconnects. We have presented the design and implementation of an innovative, compact, and low profile optical design, which contains an array of planar microlenses and which complements the active redundant alignment concept. The optical link achieves the required lateral and angular misalignment tolerances of ±1 mm and ±1° for a board separation ranging from 5 to 20 cm.

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