Gigabyte/s Data Communications with the POLO Parallel Optical Link

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1. Abstract

The progress in the development of the 10 channel POLO (Parallel Optical Link Organization) module is described. The POLO program is a consortium of Hewlett-Packard, AMP, Du Pont, SDL, and the University of Southern California to develop low cost, high performance parallel optical data links for computer clusters, multimedia, and switching systems. The design and initial performance of the 1st generation POLO module (POLO-1) have been previously reported [1]. In this paper, we discuss the overall results of the POLO-1 module as well as the design and implementation of the 2nd generation (POLO-2) parallel optical data link.

2. Introduction

Demand for interconnect bandwidth has continued to increase in computing and switching systems. Evolving communications standards such as ATM, Fiber Channel, and SCI require serial data rates approaching and often exceeding 1 Gb/s. High performance processors today have clock speeds of 300 MHz. As clock speeds and bus widths continue to increase, aggregate internal bandwidths of high performance processors will be in the multi-Gbyte/s range.

As a result, the performance of computer and communications networks are increasingly limited by the bandwidth-length and bandwidth-density product limitations of electrical interconnects. For example, in the telephone central office environment, electrical interconnects between high capacity switching systems are creating a serious bottleneck in terms of the sheer bulk of the cable required, the limited backplane real estate available for connections, and the resultant EMI created by large electrical cable bundles [2]. Optical fibers in ribbon form have much higher density as well as lower attenuation and skew than electrical cables.

Given the constraints of electrical interconnections, optical interconnect solutions at Gbyte/s data rates and distances greater than several meters will be commercially competitive. Parallel optical links also offer several advantages over serial optical links. The input and output data is inherently in parallel format, which reduces latency of mux/demux functions and simplifies system integration. A much smaller footprint is possible than with multiple serial links. Parallel optical links also amortize packaging costs over multiple channels, reducing the overall module cost per channel in comparison with serial optical links.

3. 1st Generation POLO Module Results (POLO-1)

Figure 1 shows a schematic of the POLO-1 module. The key components integrated into the package have been extensively described previously, including vertical cavity surface emitting lasers (VCSELs) [3] and Polyguide™ polymer optical waveguides [4].

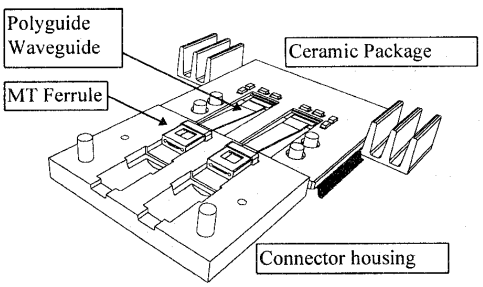

Figure 1. Schematic of POLO-1 module

Transceiver Electronics Interface

Figure 2 shows the design of the optical-electrical interface. The VCSEL/InGaAs PIN detector arrays are packaged in a 122 pin ceramic package with the transceiver ICs. Polyguide waveguides couple light between the VCSEL/PIN detector arrays and ribbon fiber using 45° out-of-plane mirrors and fiber-to-waveguide connectors. The ceramic package features impedance controlled traces and integrated resistors for termination of input ECL signals. The use of 45° optical interface allows the VCSELs and PIN detectors to be packaged in close proximity to the transceiver ICs, allowing control of electrical parasitics and GHz bandwidth operation. Because the waveguides are multimode, simultaneous alignment of 10 channels to VCSEL and PIN detector arrays is possible with loose alignment tolerances.

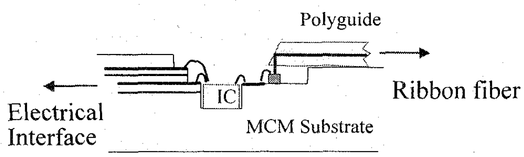

Figure 2. Optical-electrical interface

Transmitter and receiver ICs fabricated with Hewlett-Packard's HP25 bipolar process are used in the POLO module. The transmitter IC contains 10 laser drivers that use common reference voltages to set the VCSEL pre-bias and modulation currents. Several versions of the receiver IC are used, including arrays of latched digital receivers, unlatched digital receivers, and analog transimpedance amplifiers for linear testing. The latched receiver uses 9 data and 1 clock channel, where the data is synchronized to the clock at the receiver output. All receivers are dc-coupled and do not require encoded data for operation. Figure 3 shows one of the 10 channel receivers.

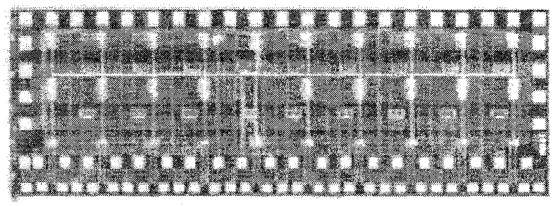

Figure 3. 10 channel receiver IC

Vertical Cavity Surface Emitting Lasers

Discrete 980 nm bottom emitting VCSELs operating in multiple transverse modes are used in the POLO-1 module. We have previously shown that such large area VCSELs emit in multiple transverse modes, leading to reduced coherence [5]. This reduces the susceptibility of the multimode fiber link to modal noise, making these sources ideal for such applications. The threshold currents of the 20 um diameter VCSELs are 3 - 4 mA. The lasers are typically pre-biased near threshold to guarantee a high extinction ratio for all channels, and modulated to peak output power of ~ 2 mW. The low relative intensity noise and reflection sensitivity of the VCSELs allows Gb/s data rates in multimode fiber links with low BER. More recently, we have characterized top emitting VCSELs at 850 nm for use in the POLO module.

Figure 4 shows an eye diagram of a 980 VCSEL biased below threshold and driven with a PRBS sequence at 622 Mb/sec. The eye is open, and the BER is < 10^{-13}.

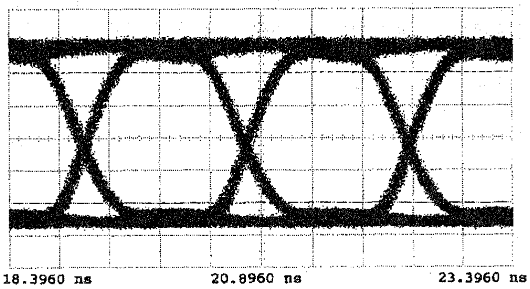

Figure 4. Eye pattern of 980 nm VCSEL at 622 Mb/s

An attractive feature of VCSELs is their ability to scale to higher data rates. Modulation of greater than 3 Gb/s per channel has been successfully demonstrated. Figure 5 shows the frequency response of a 980 nm VCSEL at two bias currents, showing a small signal 3 dB electrical frequency response of 6.5 GHz at the larger bias.

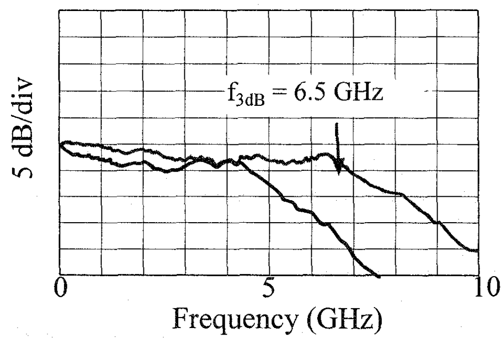

Figure 5. Frequency response of 980 nm VCSEL at two bias currents

Polymer Waveguides and Ribbon Fiber Connector

The use of polymer waveguides allows the waveguide design to be easily tailored to system requirements, including waveguide dimensions, pitch, and numerical aperture. For example, the waveguide pitch is 360 μm at the PIN detector interface and 500 μm at the VCSEL interface, but a smooth taper allows a waveguide pitch of 250 μm at the ribbon fiber interface. The width and numerical aperture of the polymer waveguide are optimized to increase coupling efficiencies and optical alignment tolerances at each interface.

The Polyguide waveguides are assembled with an MT-style ferrule and aligned to the VCSEL and PIN detector arrays on the ceramic package. To test the waveguide-ribbon fiber interface, the POLO-1 module uses an optical connector that does not incorporate the full push/pull latch mechanism.

Figure 6 shows the waveguide losses, including coupling, propagation, and mirror losses, of a single Polyguide circuit. The total optical loss between the VCSELs and PIN detectors, including connector and coupling losses, is < 6 dB. Figure 7 shows a Polyguide waveguide circuit before assembly with the MT-style ferrule.

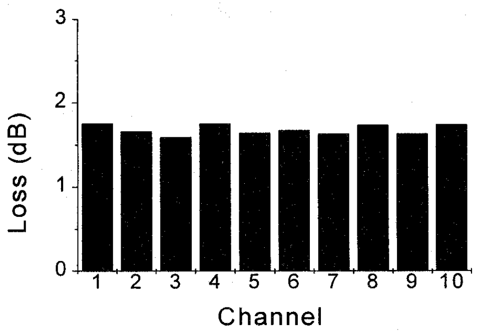

Figure 6. Loss of 3 cm waveguide (including mirror, coupling, and propagation losses)

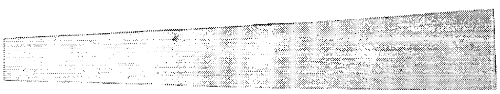

Figure 7. 10 channel Polyguide polymer waveguide

Module Performance Characterization

Figure 8 shows the assembled POLO-1 module on an evaluation board. The laser driver and receiver ICs are mounted on the ceramic substrate and wirebonded. After the VCSELs and PIN detectors are die-attached and wirebonded, Polyguide waveguides are aligned and attached for optical interface to ribbon fiber.

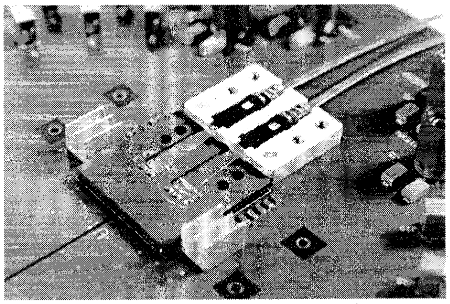

Figure 8. Assembled POLO module on board

The module is then mounted on an evaluation board for characterization. Because electrical interface to the POLO module is differential ECL, 40 SMA connections are required to operate all transmitter and receiver channels of a module simultaneously. Supply voltages of -5 and -3 volts are required for transmitter and receiver operation. An additional -2 volt supply is also required for ECL termination. Figure 9 shows the POLO-1 module on the evaluation board.

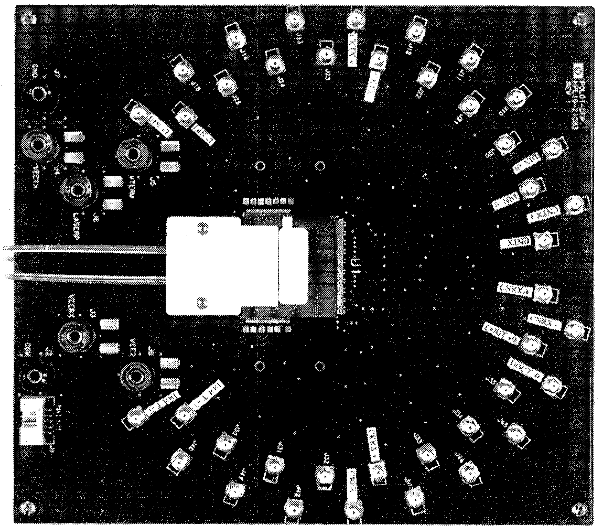

Figure 9. POLO-1 module on evaluation board

Table 1 summarizes the measured performance of the POLO-1 module. The use of low skew ribbon fiber with < 1 ps/m channel-to-channel skew [6] allows maximum interconnect lengths of up to 300 m with synchronous operation. Although the temperature range of operation has not been rigorously characterized, preliminary measurements have been encouraging.

Table 1. 1st Generation POLO Module Performance Summary	
Number of channels	10 Tx and 10 Rx (9 data/1 clock or 10 data)
Data rate per channel	0 - 622 Mb/s
Length	< 300 m
Electrical interface	Differential ECL, latched or unlatched
MCM package	Ceramic leadframe
Module width	4 cm
Wavelength	980 nm
Connector	Disconnectable MT housing
Optical interface	62.5/125 graded index ribbon fiber
Power dissipation	< 2 W or < 100 mW/channel
BER	$< 10^{-14}$

To test BER with worst-case crosstalk conditions, all 10 Tx and Rx channels of one module are operated in loopback mode, where the transmitter and receiver of one module are connected by a single ribbon fiber. A multi-channel data generator is used to modulate the 10 transmitter channels with independent PRBS streams. Figure 10 shows the eye patterns of all 10 channels in simultaneous operation at 622 Mb/s at receiver output.

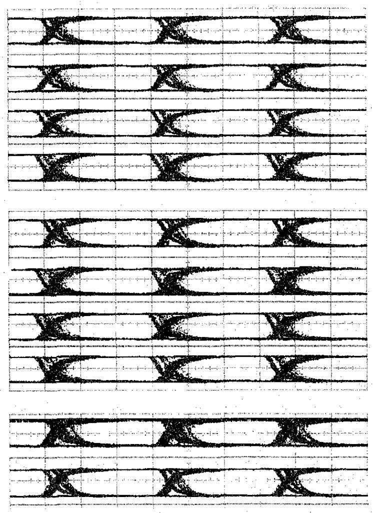

Figure 10. Output eye patterns of unlatched module at 622 Mb/s per channel

The BER for each channel was $< 10^{-11}$, and an extended measurement of one channel resulted in BER $< 10^{-14}$ with 400 m of low-skew ribbon fiber. While some pattern dependent jitter is observed, the eyes are clearly open at 622 Mb/s. The rise and fall times are < 500 ps, and channel-to-channel skew (excluding ribbon fiber skew) is < 100 ps. The phase margin for BER $< 10^{-9}$ is typically > 1 ns. Figure 11 shows 10 simultaneous output eye patterns of the module on a single oscilloscope trace. The observed accumulated jitter across all 10 channels is ~ 500 ps.

The specified maximum data rate is 622 Mb/s per channel; however, operation at data rates up to 1 Gb/s has been demonstrated with reduced eye margins.

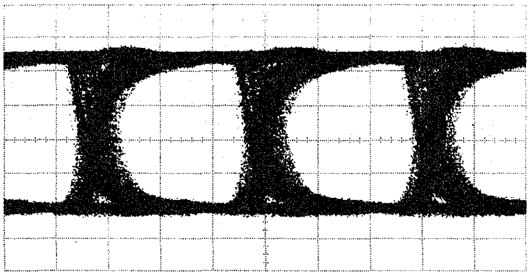

Figure 11. Output eye patterns accumulated for 10 channels at 622 Mb/s per channel

Similar results have been obtained with the latched version of the POLO-1 module. A 622 MHz clock signal synchronizes the 9 output data channels to eliminate any accumulated skew at the receiver output. Figure 12 shows the output eye patterns of a latched module at 622 Mb/s per channel.

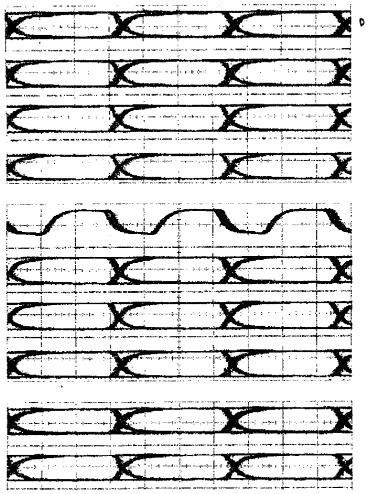

Figure 12. Output eye patterns of latched POLO-1 module at 622 Mb/s per channel

4. 2nd Generation POLO Module (POLO-2)

The second generation of POLO module (POLO-2) will incorporate several key modifications, as summarized in Table 2. POLO-2 will accommodate both 980 nm bottom emitting and 850 nm top emitting VCSELs. At 850 nm, monolithic arrays of VCSELs will be used. GaAs MSM or Si PIN detectors will be used in the receiver. Differential ECL signaling and dc-coupled electrical interface will be maintained. Two versions of the receiver (with and without output latch) will be available.

The ceramic package footprint will be reduced from 4 x 4 cm to less than 2.5 x 2.5 cm to allow an assembled module width of 1 inch. Since the reduced package footprint will limit the number of pins in a standard leadframe package, the use of ball grid arrays (BGA) is necessary for electrical interface. Standard BGA technology with 50 mil pitch is used. Finally, the module will operate at a data rate of 1 Gb/s per channel. With use of low skew ribbon fiber cables, it is expected that link lengths of up to 300 m can be accomodated without skew compensation.

Table 2. POLO-2 Performance Goals

	POLO-1	POLO-2
Number of channels	10 Tx and 10 Rx	10 Tx and 10 Rx
Length	< 300 m	< 300 m
Data rate per channel	622 Mb/s	1 Gb/s
MCM package	Ceramic leadframe	Ceramic BGA
Module width	1.6 inch	1 inch
Wavelength	980 nm	850/980 nm
Optical connector	Disconnectable MT housing	Push-pull connector

POLO-2 will also feature push-pull ribbon fiber connectors from AMP (figure 13). This connector is based on the precision molded MT array ferrule housed inside a push-pull SC style housing.

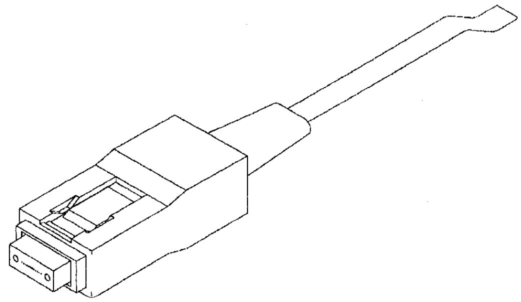

Figure 13. Push/pull ribbon fiber connector

The ribbon fiber cable uses 62.5/125 μm fiber and meets the requirements of GR-*001435 Generic Requirements for Multi-fiber Optical Connectors for Type IR Media* (Ribbonized Fiber enclosed in reinforced jacket). The design and construction of the push/pull connector is also in accordance with the optical, environmental, and mechanical testing requirements of the same Bellcore generic requirement specifications.

The uniformity of the insertion loss across 10 channels of the module will be kept below 0.6 dB throughout the service life, which includes 200 durability mating cycles. The optical insertion loss for the interface will be less than 2 dB at the end of the service life.

Figure 14 shows the design of the assembled POLO-2 module. The module housing will provide a receptacle for the push-pull. To prevent the transfer of any mechanical loads from the ribbon fiber cable to the internal module components, the module housing will mount rigidly to the printed circuit board.

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