High speed board-to-board optical interconnection

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We have demonstrated for the first time board-to-board optical interconnection having a 60 GHz bandwidth with a signal-to-noise ratio of 22 dB at 60 GHz. Board-to-board optical interconnection was realized using microprisms which had a measured coupling bandwidth of more than 250 nm. The graded index (GRIN) of the polymer waveguide allows us to implement such an interconnection scheme on an array of substrates. The implementation of a high speed on-board transceiver in connection with a polymer waveguide lens will generate a fully on-board optical interconnect involving modulation/demodulation.

We are reporting for the first time a 60 GHz board-to-board optical interconnection using polymer optical buses in conjunction with microprism couplers. An intra-board interconnection distance as long as 30 cm was previously demonstrated.[1] The result demonstrated in this paper employs two optical bus boards containing a graded index (GRIN) polymer waveguide.[2-3] Board-to-board interconnection was realized using microprism couplers made out of LaSF glass. The current performance of state-of-the-art electronic systems, especially large computers, is limited by electrical interconnects rather than the on-chip processing speed. As the number of components per chip and the processing speed increase drastically, electrical interconnection becomes inadequate on module-to-module and board-to-board levels.[4] A multi-chip module (MCM) for a high speed, highly parallel electronic system (e.g., IBM's System/390 mainframe uses an MCM that holds 121 chips, spaced about 3/8 inch apart) was implemented to minimize the speed limitation imposed on electrical interconnections (EI). However, the intrinsic characteristics of conventional electrical interconnections prohibit transmitting a 1 GHz signal farther than 1 mm.[5] The use of transmission lines involves ground plane implementation, becomes dispersive and results in significant losses from the skin effect as the speed increases.

In this paper, the demonstration of 60 GHz board-to-board optical interconnections with distances as long as 55 cm is presented. The demonstration used single-mode graded index (GRIN) polymer waveguides in conjunction with microprisms. The high speed optical signal was generated by coherently mixing two lasers, $\psi_1 = A\cos\omega_1 t$ and $\psi_2 = B\cos\omega_2 t$.

At the receiving end, the demodulation process involves a square law detector which displays the intensity of the optical signal that is [6]

$$I = \frac{e\eta}{\hbar\omega}\left[A^2 + B^2 + 2C(\omega_{beat})\cdot\cos\varphi\cdot AB\cos(\omega_{beat}t)\right] \tag{1}$$

where $\omega_{beat} = \omega_1 - \omega_2$, e is the electron charge, η is the quantum efficiency, $\hbar\omega$ is the photon energy, $C(\omega_{beat})$ is the frequency response of the detector and φ is the angle between the polarized directions of

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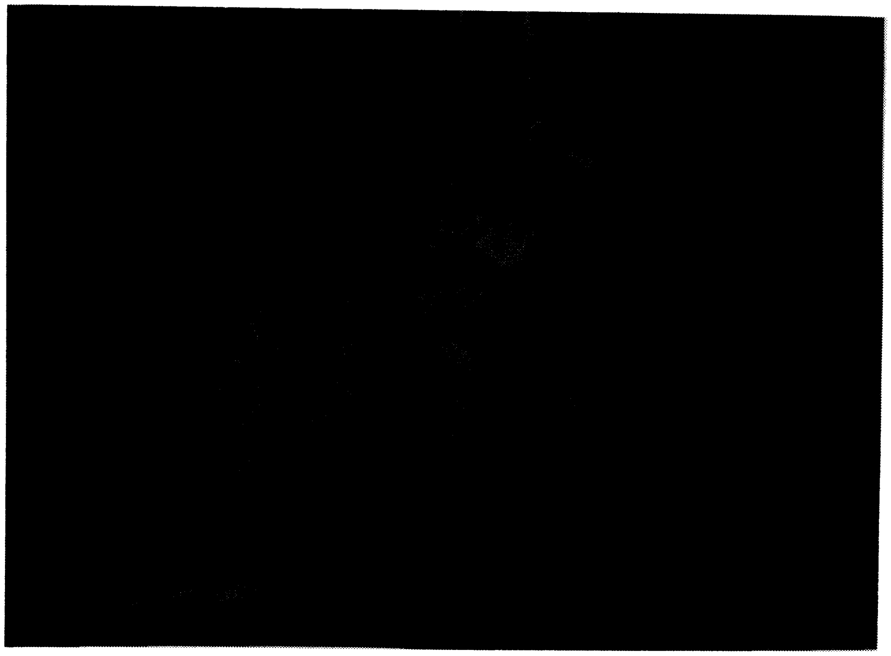
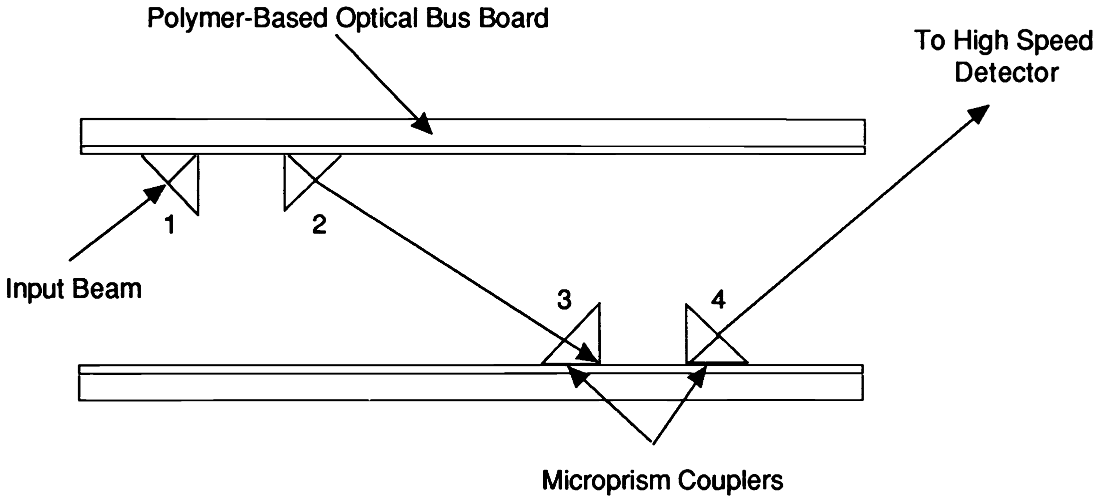
the two light waves. The frequency of the beat signal is controlled by the frequency separation of the two lasers. By coherently mixing ψ_1 and ψ_2, the detected signal represented by Eq. (1) contains a combination of the DC part and a modulated part. The result represented by Eq. (1) is equivalent to that of an optical wave modulated at a microwave frequency ω_{beat}. The two lasers we employed were a Kiton red dye laser (600 nm to 640 nm, 400 mW) and a frequency stabilized HeNe laser (632.8 nm, 0.6 mW). The wavelength of the dye laser was locked to an external-temperature-stabilized Fabry-Perot reference cavity. The linewidth and stability of both lasers was typically less than 2 MHz. Propagation of the mixed optical waves from input port to output port is illustrated in Figure 1(a). A schematic representation of Figure 1(a) is depicted in Figure 1(b). The coupling stages are not shown in Figure 1(b). Due to the GRIN property of the polymer thin film, [2,3] the optical bus boards can be made out of any substrate of interest, such as Al_2O_3, Si, GaAs, glass, PC board, etc. Our demonstration was done using BK-7 glass substrates. The measured optical insertion loss from location 1 to location 4 (Figure 1) was ~ 6 dB (excluding Fresnel reflection). The input TEM_{00} mode (location 1) and the m-dots coupled out at locations 2 and 4 are shown in Figures 2(a), (b), and (c), respectively. Formation of the well defined m-dots verified the quality of the polymer waveguide. The in-plane scattering of the optical bus board was very small. The implemented polymer waveguide has a wide optical transmission bandwidth from ~ 300 nm to ~ 2800 nm.[2] As a result, intra-board optical interconnections using UV, visible, and near IR wavelengths as the signal carrier can be realized.

The experimental setup for the high speed board-to-board optical interconnection is shown in Figure 3, where the coherently mixed optical signal is collinearly coupled into the first optical bus board through a prism coupler. The optical bus board is adjusted so that the tangential components of the EM fields are continuous at the prism/gap/waveguide interface to generate "optical tunneling". The optical beam containing the ω_{beat} (Eq. (1)) propagates across the first optical bus board and then couples out of the first board using another prism coupler. To efficiently couple the optical wave from the first optical data board to the second one, control of the profile of the beam coupled out from the output prism coupler of the first optical data board is extremely important. A good quality optical waveguide and an appropriate prism-to-waveguide attachment provided us with an output beam with well defined m-dots (Figure 2(b)) which facilitated the coupling into the second optical bus board. By employing a similar technique, a good quality m-dot was coupled out of the second optical data board (Figure 2(c)). The optical "signal" coupled out of the second optical bus board was focused onto the detector using an 10x objective lens. The demodulation scheme is shown in Figure 3. The detector is a three stage amplifier circuit consisting of a discrete InGaAs high electron mobility transistor (HEMT) [7] in series with a two stage 60 GHz MMIC amplifier [8] (a complete description of the optical mixer/amplifier will be presented elsewhere [9]). The optical mixing takes place in the active region of the discrete device. The 60 GHz output was amplified by the MMIC and fed into the waveguide via a microstrip to coaxial to waveguide transition. The 60 GHz was then downconverted to intermediate frequencies (1-2 GHz) using a directional coupler fed local oscillator (Klystron) and a waveguide mixer. Note that continuous tuning of ω_{beat} from 1 GHz to 25 GHz was demonstrated first (not shown) to maximize board to board coupling efficiency. The result, shown in Figure 4, is the heterodyne detected signal, i.e., 60 GHz-58.43 GHz. The beat signal represented by Eq. (1) is equivalent to a modulated base band signal using a high speed laser diode or an external modulator driven by a single frequency microwave source. The availability of a high speed transceiver will allow us to demonstrate board-to-board optical interconnections with fully on-board modulation and demodulation capabilities [10,11]. A GRIN polymer waveguide lens [12] can also be used to provide a diffraction-limited spot and thus achieve high speed signal detection.



(a)



(b)

Figure 1 (a) Photograph of board-to-board optical interconnection using polymer-based optical data boards in conjunction with microprisms and (b) schematic of Figure 1(a). The coupling stages are not shown.

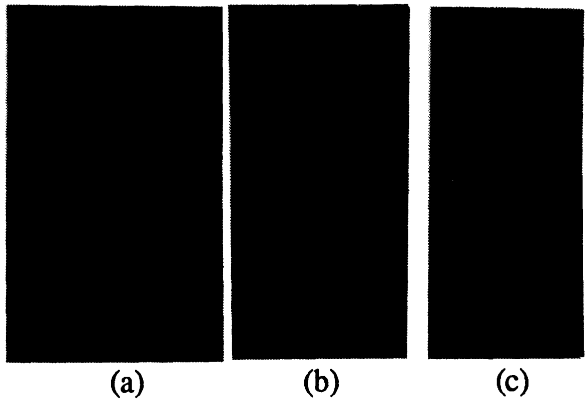


Figure 2 Near-field images of (a) TEM_{00} laser light at location 1 (Figure 1(b)), (b) mode dot at location 2, and (c) mode dot at location 4.

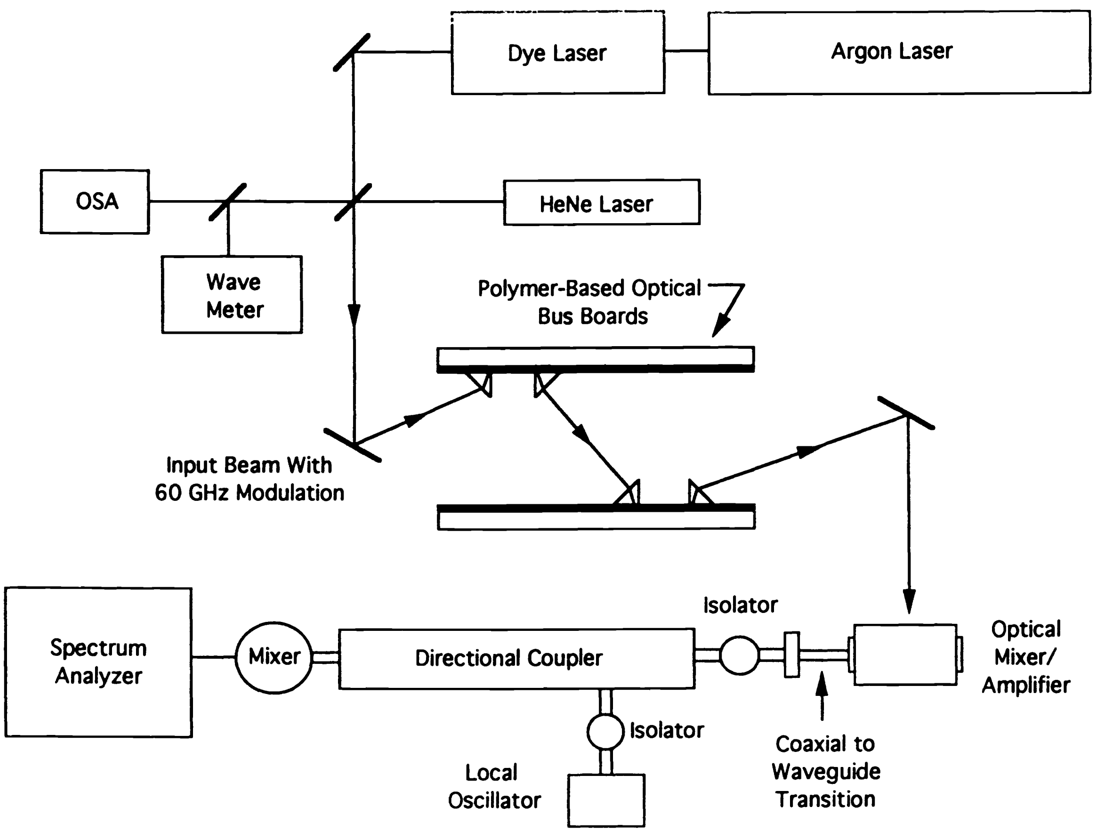


Figure 3 Generation, transmission, and detection of 60 GHz signal for 55 cm board-to-board optical interconnection.

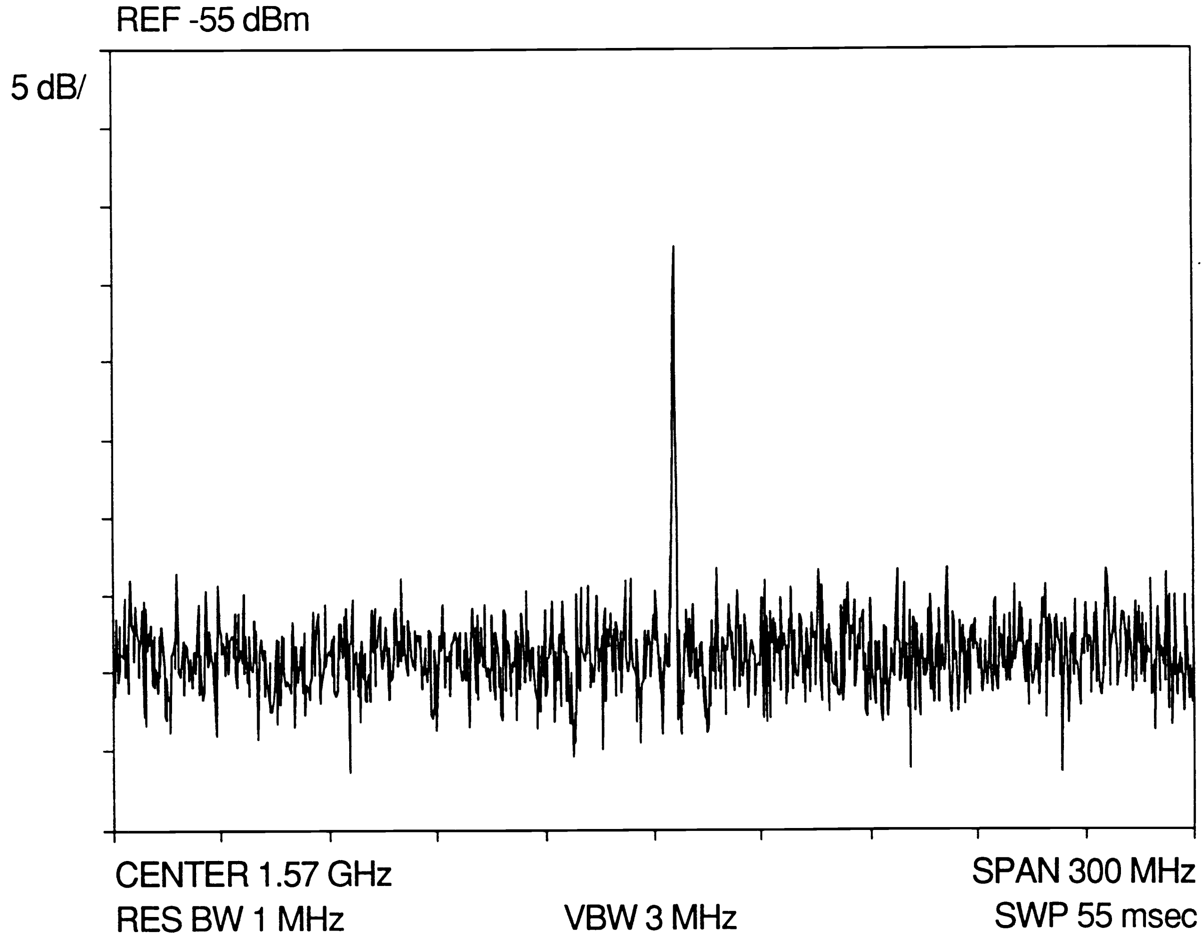


Figure 4 60 GHz signal detected at location 4 (Figure 1(b)). A 22 dB signal-to-noise ratio is clearly indicated.

The experimental results demonstrated in this paper conclude that the GRIN polymer waveguide can be used as a high speed optical bus for board-to-board optical interconnection with speeds as high as 60 GHz and bit error rates (BER) of 10^{-10} (22 dB signal-to-noise ratio). It should be noted that the limit on speed was imposed by the system power budget rather than the polymer-based optical bus board. A 1 GHz board-to-board optical interconnection through free space was previously demonstrated [13]. Here a 60 GHz board-to-board optical interconnection involving a single-mode polymer waveguide is reported for the first time. For the 3-D optical interconnection demonstrated in this program, board-to-board interconnections were realized through free space rather than an optical backplane [14]. Optical interconnections through a backplane introduce an extra degree of material dispersion and thus impose a more stringent speed limit for 3-D optical interconnections. 3-D optical interconnections using holographic optical elements (HOEs) turn out to be impractical [4] due to the required phase-matching condition associated with them. Such coupling devices are intrinsically narrow-band which strictly limits the availability of light sources. To cover the required interconnection distances using HOE while still maintaining a good power budget, the entire area of the detector has to be enlarged to compensate for the deviation of the optical beam propagation due to the shift of optical wavelength. Consequently, the speed of 3-D optical interconnections involving HOEs will be significantly reduced. On the other hand, the microprism we employed is a wide-band coupler. By fixing the input beam at the coupling angle which is phase-matched to the effective index of the guided wave, a 3 dB coupling bandwidth of more than 250 nm was experimentally confirmed using a Ti-Sapphire laser. Figure 5 shows the demonstrated experimental results. Note that such wide-band coupling is realizable only if the material dispersion of the GRIN polymer waveguide and the prism as a function of wavelength have a coherent pace within the full spectrum of optical wavelength tuning. The selection of a microprism with this dispersion characteristic is a paramount factor in the results presented here.

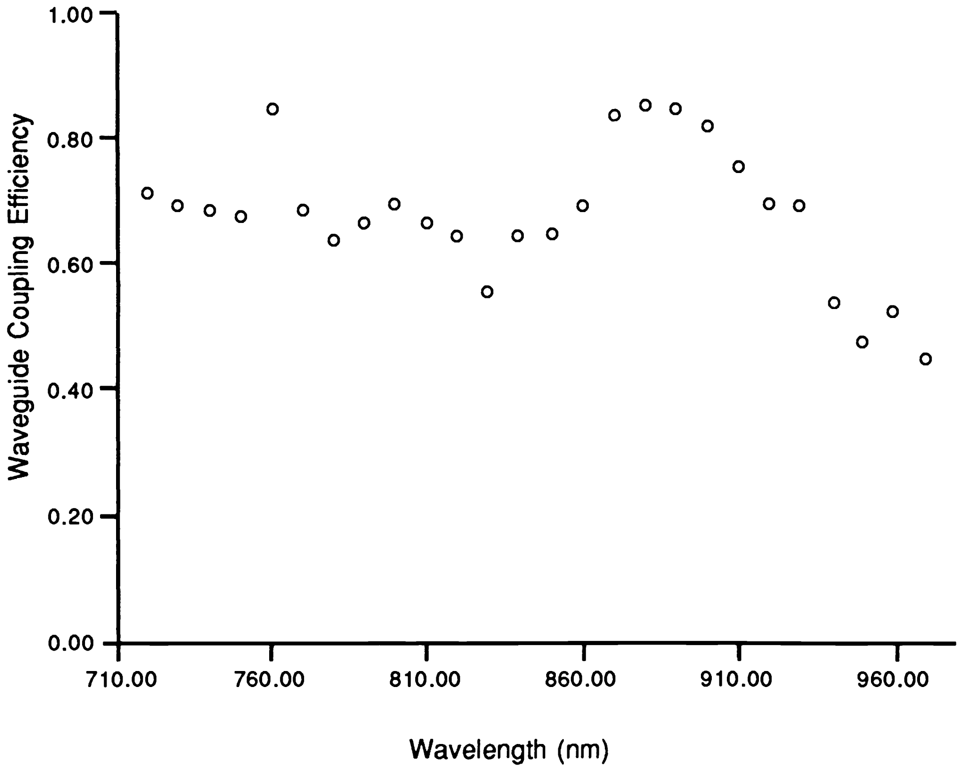


Figure 5 Experimental result of free space to polymer-based optical bus board coupling using a microprism. A 3 dB bandwidth of more than 250 nm is shown.

The results demonstrated in this paper represent the first 3-D optical interconnection network involving single-mode GRIN polymer waveguides and microprism couplers through which highly parallel wide band signals can be routed efficiently. Figure 6 shows a schematic of the interconnection network. Note that intra-MCM (multi-chip module) interconnection through polymer waveguides and inter-MCM interconnection through polymer waveguide (intra-board) and free space (inter-board) are feasible using the presented technology. Maturization of flip-chip technology [15] and epitaxial liftoff (ELO) technology [16] provide us easy means to realize a fully integrated optical interconnection system.

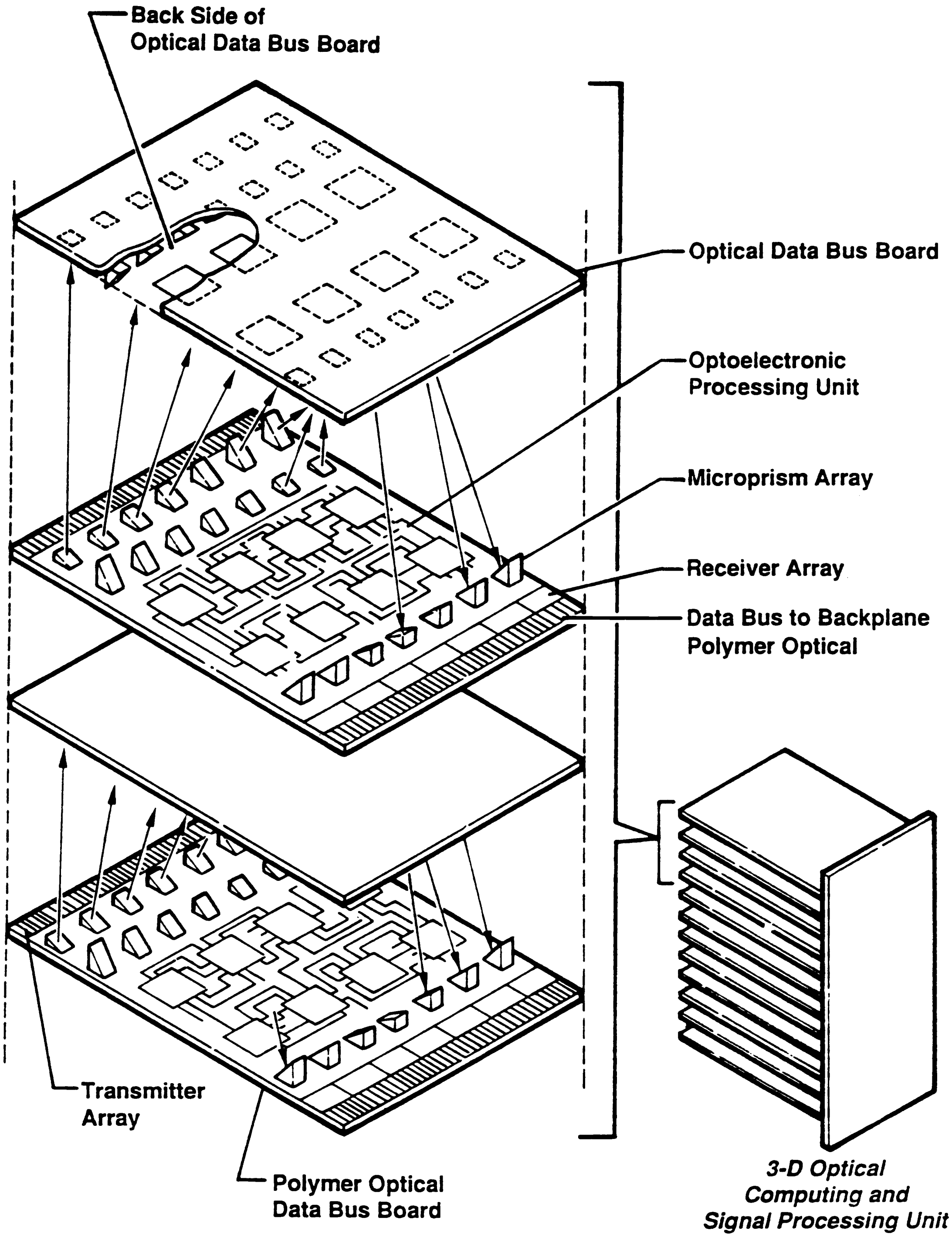


Figure 6 Schematic of a highly parallel board-to-board optical interconnect system.

In summary, we are reporting for the first time a 60 GHz board-to-board optical interconnection using polymer optical buses in conjunction with wide-band microprism couplers. A signal-to-noise ratio of 22 dB was experimentally confirmed, which is equivalent to a BER of 10^{-10}. The 60 GHz CW microwave signal was generated by coherently mixing light from two lasers. The beat signal, which was 60 GHz in our demonstration, is similar to an optical signal modulated by either an external modulator or a laser diode using a 60 GHz single frequency microwave as the modulation source. Implementation of transmitter and receiver on the optical data board will allow us to demonstrate a fully on-board optical interconnection scheme involving modulation and demodulation processes. Implementation of a polymer waveguide lens on the optical data board will provide us with a diffraction-limited spot and thus ease the demodulation criterion. The reported speed limit is due to the system power budget rather than the GRIN polymer waveguide. Finally, the combination of a GRIN polymer waveguide and a LaSF microprism provided us with a 250 nm free space to optical data board coupling bandwidth, which is two orders of magnitude higher than for an HOE. The technology presented herein is useful for intra-MCM, inter-MCM, and board-to-board optical interconnects.

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