60 GHz board-to-board optical interconnection using polymer optical buses in conjunction with microprism couplers

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We have demonstrated for the first time 60 GHz wide-band board-to-board optical interconnection with a signal-to-noise ratio of 22 dB. The total interconnection distance is 55 cm from the input coupling prism to the detector. Board-to-board optical interconnection was realized using microprisms which had a measured coupling bandwidth of more than 250 nm. The graded index of the polymer waveguide allows us to implement such an interconnection scheme on an array of substrates. The elimination of backplane interconnection greatly enhances the interconnection speed. 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 intraboard 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 multichip module (MCM) for a high-speed, highly parallel electronic system (e.g., IBM's System/390 mainframe uses a MCM that holds 121 chips, spaced about 3/8 in. apart) was implemented to minimize the speed limitation imposed on electrical interconnections (EI). However, the intrinsic characteristics of conventional electrical interconnections jeopardize transmitting a 1-GHz signal farther than 1 mm.[5] The use of transmission lines involves ground-plane implementation, which becomes dispersive and results in significant losses from the skin effect as the speed increases.

In this letter, the demonstration of 60 GHz board-to-board optical interconnections with distances as long as 55 cm is presented. The demonstration used single-mode 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 as a photocurrent[6]

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

where $\omega_{\rm beat} = \omega_1 - \omega_2$, e is the electron charge, η is the quantum efficiency, $\hbar\omega$ is the photon energy, $C(\omega_{\rm beat})$ is the frequency response of the detector, and φ is the angle between the polarized directions of 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 $\omega_{\rm beat}$. The two lasers we employed were a Kiton red dye laser (600–640 nm up to 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 Fig. 1(a). A schematic representation of Fig. 1(a) is further depicted in Fig. 1(b). The coupling stages are not shown in Fig. 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 (Fig. 1) was $\sim$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 Figs. 2(a), 2(b), and 2(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 polymer waveguide implemented has a wide optical transmission bandwidth from $\sim$300 to $\sim$2800 nm.[2] As a result, intraboard optical interconnections using ultraviolet, visible, and near-infrared wavelengths as the signal carrier can be realized.

The experimental setup for the high-speed board-to-board optical interconnection is shown in Fig. 3, where the

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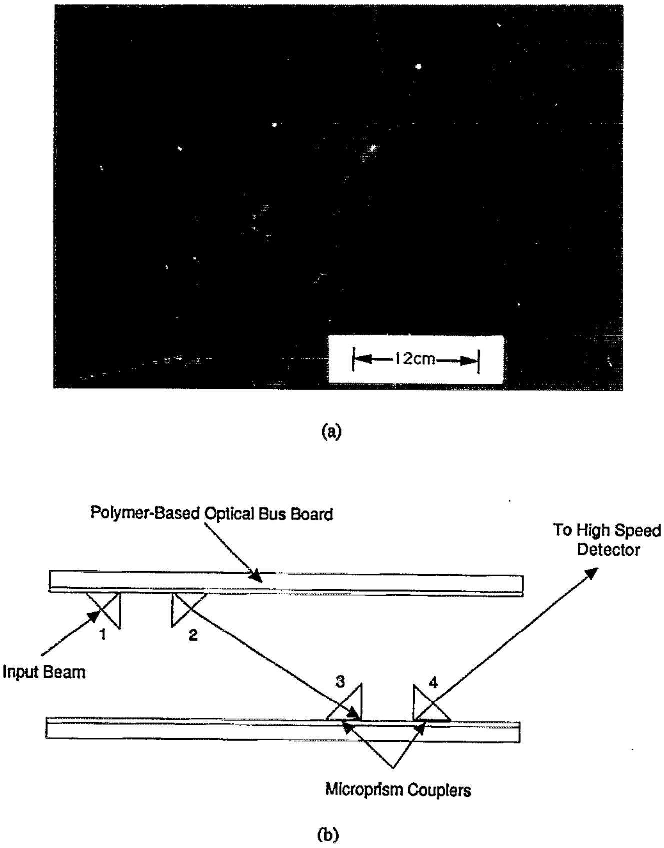

FIG. 1. (a) Photograph of board-to-board optical interconnection using polymer-based optical data boards in conjunction with microprisms. (b) Schematic of (a). The coupling stages are not shown.

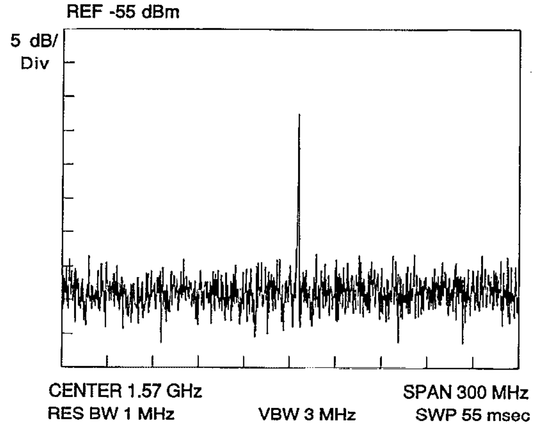

FIG. 3. Generation, transmission, and detection of 60 GHz signal for 55-cm board-to-board optical interconnection.

coherently mixed optical signal is collinearly coupled into the first optical bus board through a prism coupler. The optical bus board is adjusted such that the tangential components of the electromagnetic 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 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 [Fig. 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 [Fig. 2(c)]. The optical "signal" coupled out of the second optical bus board was focused onto the detector using an 10× objective lens. The demodulation scheme is shown in Fig. 3. The detector is a three-stage amplifier circuit consisting of a discrete AlGaAs/InGaAs high-electron-mobility transistor (HEMT)[7] in series with a two-stage 60 GHz millimeter-wave monolithic integrated circuit (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 HEMT device. The 60 GHz output was amplified by the MMIC and fed into waveguide via a microstrip to coaxial to waveguide transition. The signal was then downconverted to intermediate frequencies (1–2 GHz) using a directional coupler fed local oscillator (klystron) and a waveguide mixer. In the initial phases of this experiment, continuous tuning of ω_{beat} from 1 to 25 GHz was demonstrated to establish the large bandwidth capability of this system. We then switched to the highest frequency of our new detection system and the result shown in Fig. 4 is the heterodyne detected signal at 60 GHz. As previously mentioned, 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.

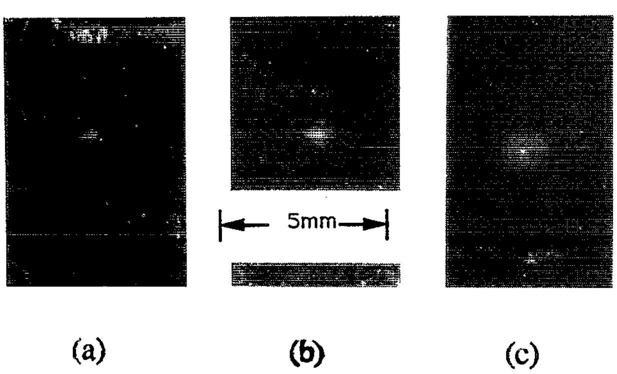

FIG. 2. Near-field images of (a) TEM_{00} laser light at location 1 [Fig. 1(b)], (b) mode dot at location 2, and (c) mode dot at location 4.

The experimental results demonstrated in this letter conclude that the GRIN polymer waveguide can be used as a high-speed optical bus for board-to-board optical in-

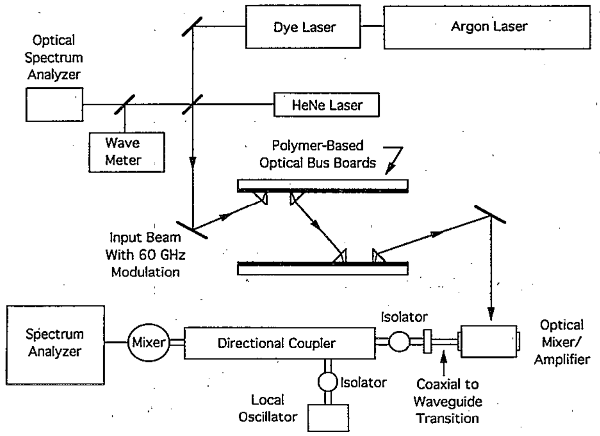

FIG. 4. 60-GHz signal detected at location 4 [Fig. 1(b)]. A 22-dB signal-to-noise ratio is clearly indicated.

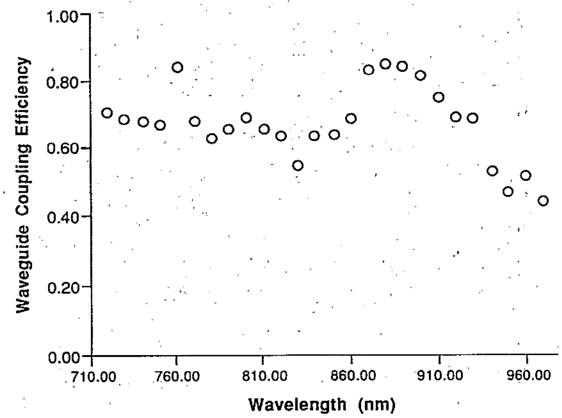

FIG. 5. Experimental result of free space to polymer-based optical bus board coupling using a microprism. A 3-dB bandwidth of more than 250 nm is shown.

terconnection 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 three-dimensional (3D) 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 3D optical interconnections. 3D 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. 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 has 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.

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 BER of 10^{-10}. The beat signal, which was 60 GHz in our demonstration, is equivalent 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 a polymer waveguide lens onto the optical data board will provide us with a diffraction-limited spot and thus ease the demodulation criterion. 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.

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