Passive and Active Components for Intra- and Inter-Board Level Optical Interconnects and Packaging

Ray T. Chen
Microelectronic Research Center, Department of Electrical and Computer Engineering,
The University of Texas at Austin, Austin, TX 78758, USA
chen@ece.utexas.edu
http://www.mrc.utexas.edu/chen.html

Summary

The speed and complexity of integrated circuits are increased rapidly as integrated circuit technology advancesfrom very large-scale integrated (VLSI) circuits to ultra-large-scale integrated (ULSI) circuits. As the number of components per chip, the number of chips per board, themodulation speed, and the degree of integration continue to increase, electrical interconnects are facing their fundamental bottlenecks, such as speed, packaging, fanout, and power dissipation. Multichip module (MCM) technology is employed to provide higher data transfer rates and circuit densities. The employment of copper and lower dielectric constant materials can release the bottleneck for next several years. However, the interconnection roadmap still predicts a major bottleneck in the near future. The employment of optical interconnects will beone of the major alternatives for upgrading the interconnection speed whenever conventional electrical interconnection fails to provide the required bandwidth.

Machine-to-machine interconnection has already been significantly replaced by optical means. The major research thrusts in optical interconnection are in the backplane and board level where the interconnection distance, the associated parasitic RLC effects, and the large fanout induced impedance mismatch are to jeopardize the bandwidth requirements. Optical interconnection has been widely agreed as a better alternative to upgrade the system performance. However, reliability and packaging compatibility of many demonstrated optical interconnect systems have impeded the integration of optical interconnect into a real system. For example, the board-level optical interconnections reported in [4] are all using hybrid approach where both electronic and optoelectronic components are located at the surface of the board. Such an approach makes the packaging difficult and costly. Furthermore, the employment of free space instead of guided-wave optical interconnection reported in [4]–[6] makes the system vulnerable in harsh environment.

In this paper, we present a new system architecture to solve these problems and the experimental results aimed at fulfilling such an architecture. In contrast to previous approaches, a fully embedded board-level guided-wave optical interconnection is presented in Fig. 1, where all elements involved in providing high-speed optical communications within one board are shown. These include a vertical-cavity surface-emitting laser (VCSEL), surface-normal waveguide couplers, and a polyimide-based channel waveguide functioning as the physical layer of optical bus and a photoreceiver. The driving electrical signal to modulate the VCSEL and the demodulated signal received at the photoreceiver are all through electrical vias connecting to the surface of the PC board. By doing so, all the real estate of the PC board surface are occupied by electronics, and therefore one only observes the performance enhancement due to the employment of optical interconnection but does not worry about the interface problem between electronic and optoelectronic components, unlike conventional approaches.

To provide the needed building blocks for the architectureshown in Fig. 1, the research findings of polymer based waveguides, waveguide couplers, high-speed thin-film transmitters using VCSEL's, and thin-film receivers operating at 850 nm are presented. The fully embedded structure [1] makes the insertion of optoelectronic components into microelectronic systems much more realistic when considering the fact that the major stumbling block for implementing optical interconnection onto highperformance microelectronics is the packaging incompatibility. The 45° total internal reflective (TIR) micro-mirrors were adopted to couple light from a VCSEL into waveguide array, and then to a PIN photodiode. To get a soft mold with 45° micro-mirror couplers, the master waveguide structure was cut on both ends by specially designed tool. The master waveguide structure was put on a 45° tilted stage with a temperature at 120

°C. A horizontal sliding microtome blade cut 12 channel waveguides simultaneously. The PDMS (Sylgard 184, Dow Corning) was chosen as a soft mold material. The PDMS was poured on the master waveguide structure and cured. Surface relief waveguide patterns with 45° micro-mirror couplers were transferred from the master waveguide structure to the soft mold.

A flexible waveguide film was fabricated by the soft mold process. The core material (SU-8) was poured on the heated soft mold and then excess SU-8 was scraped out. The soft mold filled with SU-8 was covered by the Topas™ 6015 (cyclo-olefin-copolymer) film, as a bottom cladding layer. The core waveguide structure was transferred from the soft mold to the Topas™ 6015 film by the hot-press machine. A flexible waveguide film without the top cladding layer was exposed to UV to cross-link the SU-8 and then the surfaces of the 45° micro-mirror were deposited with the aluminum (Al) to ensure the total refraction. Finally, the top cladding layer was spin coated on the film. The EMCORE's 12 channel, 850 nm wavelength VCSEL and PIN photodiode were used as I/O sources for a flexible waveguide film. The initial substrate thickness (200 μm) of the VCSEL was reduced to 50 ~ 70 μm for managing the thermal resistance of the VCSEL. Apertures of optoelectronic device were precisely aligned with I/O windows of the 45° micro-mirror couplers and fixed by a UV curable adhesive. Fig 2 shows an integrated VCSEL array which has a thinned substrate. The conventional PCB lamination processes were applied to interpose a flexible waveguide film between PCB layers.

To fulfill a reliable optical interconnection, electrical to optical signal conversion can be realized in two ways: 1. direct modulation of a laser diode and 2.indirect modulation of an external modulator. The first approach is to directly modulate a laser diode which is presented in this paper. The 2nd approach is to regard the semiconductor laser as an external CW light source generating a constant optical power source. For analog modulation, the 2nd approach is device of choice due to the fact that we can easily engineer the transfer curve to the required linearity, an important feature for analog modulation of optical signals. Silicon provides us with a ready to use nano-fabrication technology [3] to build nano-photonic devices. We thus further investigated the feasibility of building an active silicon EO device that can be fully embedded inside an interconnect platform shown in Figure 1. A silicon nano-photonic crystal waveguide based electrooptic waveguide modulator is further presented in this paper [4]. Photonic crystals (PhCs) are a class of artificial optical materials with periodic dielectric structures, which result in unusual optical properties. PhCs now show promise to be a key platform for future optical integrated circuits [5-7]. Due to the unique properties of PhCs, the size of many optical components is anticipated to be greatly reduced by employing PhC structures, such as photonic crystal waveguides. In the most commonly employed configuration, a photonic crystal waveguide is formed by introducing a line defect into a two-dimensional (2D) PhC slab. In such PhC waveguides, light is confined by a combination of in-plane PBG confinement and vertical index guiding. A size reduction mechanism based on slow group velocity in photonic crystal waveguides has been discussed for an array of optical devices. Notomi *et al.* firstly demonstrated low group velocity and high group velocity dispersion using silicon PhC slab line defect waveguides. Several other groups also demonstrated this effect in both line-defect and coupled-cavity PhC waveguides.

In the context of microelectronics, silicon has been the optimal material for microelectronics for a long time, but it has only relatively recently been considered as an option for photonics. Silicon is transparent in the range of optical telecommunication wavelengths, 1.3 μm and 1.55 μm, and has high refractive index that allows for the fabrication of high-index-contrast nano-photonic structures. In addition, as silicon photonics technology is compatible with conventional complementary metal-oxide-semiconductor (CMOS) processing, monolithic integration of silicon photonic devices with advanced electronics on a single silicon substrate becomes possible. Optical modulators are pivotal components in silicon based optoelectronic integrated circuits. Most silicon electro-optic modulators are based on plasma dispersion effect, through which carrier concentration perturbation results in refractive index change. There are a number of ways to vary the carrier concentration in silicon including carrier injection and capacitive coupling though the metal-oxide-semiconductor (MOS) field effect. For broadband optical intensity modulators, the silicon Mach-Zehnder Interferometer (MZI) structure that converts a phase modulation into an intensity modulation is widely used. However, conventional silicon MZI modulators are based on rib waveguides, which usually need one-half to several millimeters to achieve the required phase shift in MZI structures. The reason is that propagation constant perturbation, $\Delta\beta$, is fairly low, thus requiring larger rib waveguide length, L, to achieve required phase shift, $\Delta\phi = \Delta\beta \times L$.

The extraordinary dispersion of photonic crystal (PhC) waveguides offers an unprecedented opportunity for developing ultra-compact MZI modulators. Consider a typical dispersion relation for a PhC waveguide mode shown in Fig. 3. If the refractive index of the waveguide core material (*i.e.* silicon) varies by an amount of Δn, the dispersion curve will shift vertically by an amount $\Delta\omega_o$. The propagation constant β_{PC} of PhC waveguide changes as $\Delta\beta_{PC} = \frac{d\beta_{PC}}{d\omega}\Delta\omega_0$, which grows significantly whenever the group velocity $\frac{d\omega}{d\beta_{PC}}$ approaches zero, e.g. on the right-most segment of dispersion curve in Fig. 3. Such an extraordinary growth of $\Delta\beta_{PC}$ directly leads to a significant enhancement of phase modulation efficiency because the phase change is related to the change of propagation constant and waveguide length L as $\Delta\phi_{PC} = \Delta\beta_{PC} \times L$. One can easily enhance $\Delta\beta_{PC}$ by more than 100 times using a photonic crystal waveguide. Therefore, a 100 times shorter PhC waveguide can produce the same phase change as a long conventional waveguide.

An ultra-compact silicon electro-optic modulator was experimentally demonstrated based on silicon photonic crystal (PhC) waveguides for the first time to our knowledge. Modulation operation was demonstrated by carrier injection into an 80 μm-long silicon PhC waveguide of a Mach-Zehnder interferometer (MZI) structure. The π phase shift driving current, I_π, across the active region is as low as 0.15 mA, which is equivalent to a V_π of 7.5 mV when a 50 Ω impedance-matched structure is applied. Further results will be presented in the conferences and future publications.

All the contributions of PhD students and postdocs in Chen's group are acknowledged and their names are listed in the references 1, 2, and 4.

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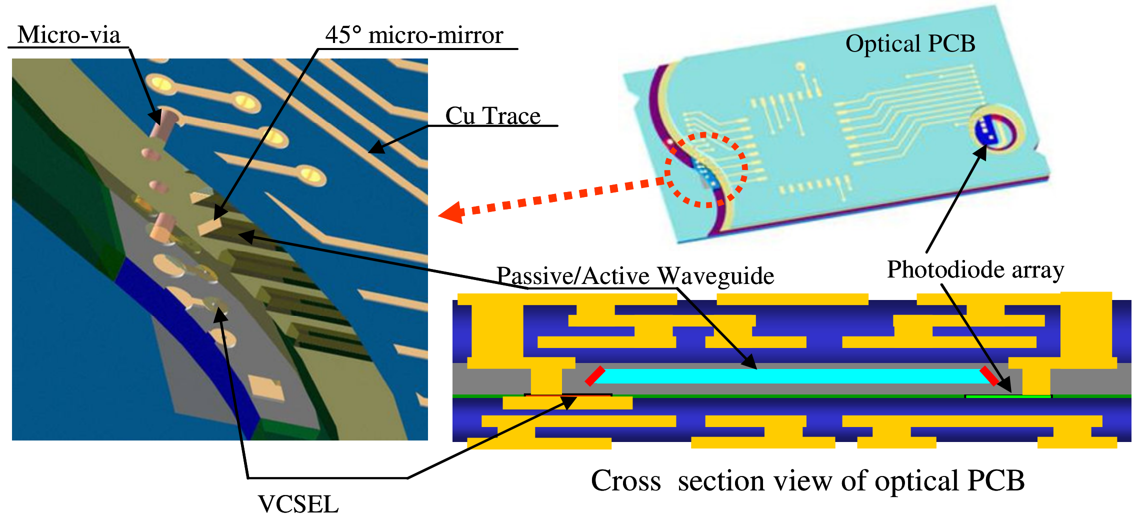
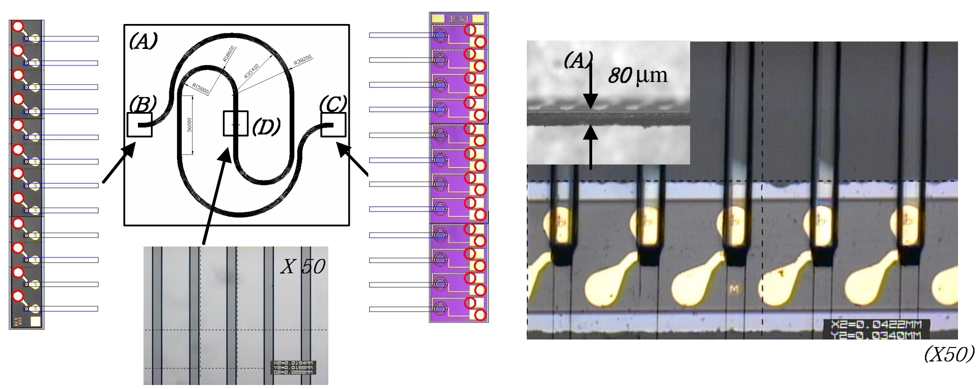


Fig. 1. The fully embedded guided wave optical interconnect system architecture. A PC board with several interconnection layers with schematic of the side view of the vertical integration layers with passive/active waveguides, VCSEL, photodetector, waveguide coupler, electrical vias, and other electrical interconnection layers are clearly shown.



(a) (b)

Figure 2. (a) (A)A flexible optical waveguide film, (B)12 channel VCSEL array, (C)12 channel PIN Photodiode array, (D)12 channel polymer waveguide structure. Figure 2(b) A Integrated VCSEL array on a flexible optical waveguide film. (b) A side view of a substrate thinned VCSEL. [2]

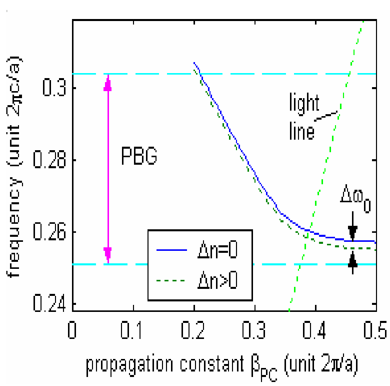


FIG. 3. Dispersion relation of a guide mode of a photonic crystal waveguide [4]