Invited Paper

Guided-wave Optoelectronic Interconnects: Their Potential and Future Trend

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ABSTRACT

We present in this paper the research status of polymer-based photonic integrated circuits (PICs) and their applications for VLSI optoelectronic interconnects. Demonstrated features of polymer-based PICs are delineated with GaAs and $LiNbO_3$ integrated photonic devices as references. These unique features, including longer interconnection length, larger phase modulation index, graded-index (GRIN) characteristic, massive fanout capability and cost-effectiveness, make the polymer-based PICs very attractive for an optoelectronically interconnected VLSI system. The usefulness of polymer-based PICs for VLSI optoelectronic interconnects relies on not only the system requirements but also the processing temperatures over which polymer-based photonic devices are fabricated and then assembled. Realizing the fact that the speed of electrical interconnects is already lower than the clock speed of the state-of-the-art high performance processors, the author expect that electrical interconnects that are unable to fully exploit the speed provided by the processors will be gradually replaced by optoelectronic interconnects. Optical bus design rules are provided in this paper to optimize the interconnection length while maintaining low cross talk and maximum bus packing density. Optoelectronically interconnected inter-MCM (multi-chip module) and intra-MCM will be the future research trend of optoelectronic interconnects. Intra-board and backplane optoelectronic interconnects represent the major mile stones for the realization of these schemes.

The intrinsic limitations of the current generation of computers have led researchers to seriously consider new computing architectures based on optoelectronic interconnects. The basic limitations of VLSI electrical interconnects include subjection to electromagnetic interference (EMI) and pulse (EMP) effects, clock skew, RC time constants and even the distributed line RLC time constant. In particular, when the time bandwidths provided by electrical interconnects are too wide they are very difficult to manage. As cycle time and pulse widths shrink, the bandwidth needed to preserve the rising and falling edges of the signals increases. This makes using bulky, expensive, terminated coaxial interconnections a necessity. Clock skew is the next most important performance limitation of conventional computers, especially on the board-to-board interconnect level. It slows the signal processing and occurs when signals from different parts of a circuit arrive at a gate at slightly different times, a difference of nanoseconds. This input skew causes a gate to generate an erroneous output. These intrinsic bottlenecks associated with electrical interconnect represent some of the major threats for high performance computing and data management. For air-borne and space-borne applications, optoelectronic interconnects can provide a much better communication bandwidth while maintaining a significant weight improvement over electrical interconnects.

The push for higher speed forces shorter cycle times and this, in turn, limits the maximum differences in processor interconnection lengths. For example, this maximum difference in the Cray-1 is 6 inches. All interconnections less than this length are padded with gate delays equivalent to that of a 6-inch interconnection. This restriction on the

0-8194-1448-4/94/$6.00

interconnection length complicates both the physical and electrical designs of such a processor and points to some of the difficulties which will require resolution for the next generation of processors. The accepted approach is to wait for the inputs to settle before utilizing the output of a gate. This input settling time is dependent on the amount of time it takes to fully charge the input connection and is quite different from the time it takes for a pulse to propagate down the interconnection. This charging time is a function of the resistance, capacitance and inductance of the interconnection and the input of the gate. Presently, the RC time constant is already slower than the time it takes for a transistor to switch. As a result, it is very difficult to exploit the performance of ultrafast logic gates in a circuit with traditional interconnects. The difficulties associated with this RC or RLC-dominated settling time are not solved by VLSI. As the length of a wire shrinks by a factor of S and the cross-sectional area of the wire is reduced by a factor of S^2, the capacitance of the wire decreases by a factor of S while the resistance increases by a factor of S. The RC time constant and thus the input charging time remain the same, independent of scaling. Various interconnect hierarchies are shown in Figure 1 where the replacement of electrical interconnects by optical means has already occurred in machine-to-machine interconnect. Two most active research areas in optoelectronic interconnects are board-to-board and inter-module levels which represent the most serious bottlenecks of VLSI-based electrically interconnected high performance computing and signal processing systems.

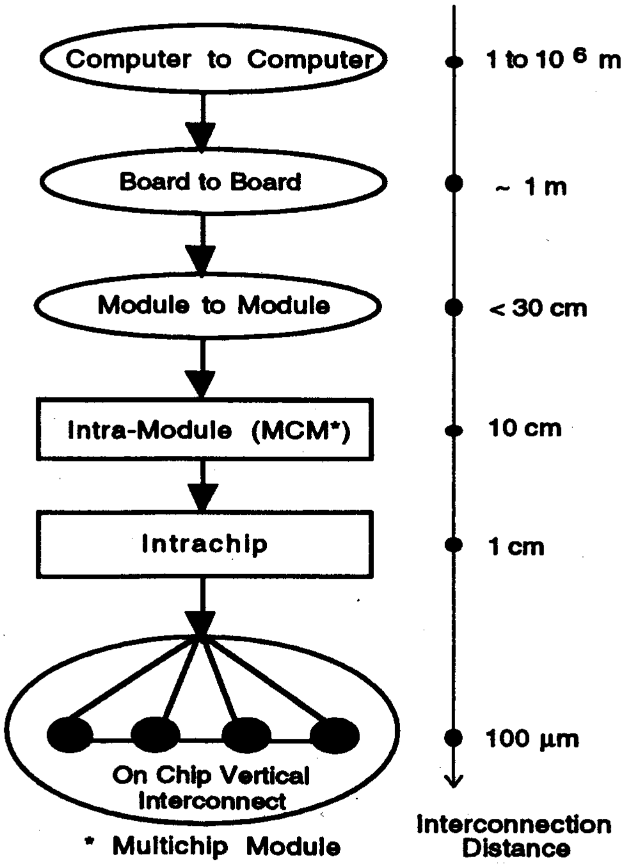

Figure 1 Various Interconnection Hierarchies

The development of advanced optical materials and devices that can focus, modulate, multiplex, transmit, receive, demultiplex and demodulate optical signals, will be pivotal for the realization of a reliable VLSI optoelectronic interconnect system. To date, major efforts have focused on the development of hybrid and monolithically integrated devices and systems in the Si, $LiNbO_3$ and III-V material systems, respectively. Si-based VLSI technology is mature but the intrinsic properties such as indirect band gap, no electrooptic effect, etc., make the effort of fabricating Si-based monolithically integrated optoelectronic circuits impractical. $LiNbO_3$- and GaAs-based active photonic devices such as electrooptic modulators and laser diodes, are needed to provide an optoelectronically interconnected system involving VLSI circuits. A number of technology-related issues, however, currently impede further progress. First, both $LiNbO_3$ and III-V semiconductors are incapable of producing the large index modulations that are required to create multiplexed phase gratings, which is important for clock signal distribution in optoelectronically interconnected VLSI systems. Second, the requirements of lattice-matching have severely restricted the number, size and types of materials that can be grown on top of the III-V compound substrates and epilayers. This effect results in a serious limitation on interconnect length and hierarchies. Third, dielectric constants of these materials are highly dispersive when compared with polymeric materials. The walk-off between optical and microwave indices is high and thus the modulation bandwidth of a travelling wave electrooptic modulator becomes low. Fourth, the interconnection length is limited by the dimension of inorganic crystal itself. Module -to-module and backplane optoelectronic interconnects may require an interconnect length well above such a dimension. For instance, module-to-module interconnects may require an interconnect length well above 12 inches and therefore makes the requirement of other optical mediums that can provide longer interconnect lengths a necessity. Lastly, device yields have been relatively low, while costs associated with the growth and processing of related microstructures have been high. Hence, the development of new, low-cost materials that can get rid of the above mentioned problems and processed into microstructural optoelectronic components, such as waveguides, gratings and EO modulators will be invaluable to the optoelectronic integration efforts for future VLSI-based systems.

An array of guided wave device research programs have been concentrated on polymer-based materials to alleviate the problems affiliated with inorganic materials. Polymer molecules are formed by combining a myriad of monomers. Therefore, by definition, there is an infinite number of polymers can be formed. The polymeric materials suitable for guided wave device application in general and for optoelectronic interconnection in specific, are the ones that demonstrated acceptable optical and mechanical properties. Both passive and active polymer-based guided wave devices have been demonstrated using different polymeric materials. In this paper, I report on the development and study of a new polymer-based passive and active guided wave devices aimed at VLSI Optoelectronic interconnect applications . It overcomes many of the problems associated with the fabrication of conventional microstructural thin-films, as described above, and shows promise for becoming a new building block in optoelectronically interconnected VLSI systems. The device features to be delineated in this paper are summarized in Table 1 with the device features of $LiNbO_3$ and GaAs as references. Both passive and active photonic circuit elements are delineated. Demonstrated performance features of these polymer-based guided wave devices are addressed sequentially in this paper. On-going research programs representing the major efforts in VLSI optoelectronic interconnects from both industry and academia are presented in the conference.

Table 1

Demonstrated Features of Polymer-Based Photonic Integrated Circuits, at the Microelectronics Research Center of the University of Texas, Austin, with GaAs and LiNbO$_3$ Devices as References

	TECHNOLOGY		
Features	Polymer-Based	GaAs	LiNbO$_3$
1. Planar Waveguide	Yes	Yes	Yes
2. Channel Waveguide	Yes	Yes	Yes
3. Waveguide Propagation Loss	< 0.1 dB/cm[a]	0.2 to 0.5dB/cm	< 0.1 dB/cm
4. OEIC Size	Unlimited [b]	Limited [b]	Limited [b]
5. Modability	Yes[c]	No	No
6. Channel Waveguide Packaging Density (channels/cm)	High [d]	High[d]	High[d]
7. Implementation on Other Substrates	Easy [e]	Difficult [f]	Difficult [f]
8. Large Area Multiple-Guiding Layer on Single Substrate	Yes	No	No
9. Formation of Multiplexed Grating	Yes [g]	No	No
10. Waveguide Lens	Yes	Yes	Yes
11. Dielectric Constant Dispersion	Low [h]	High	High
12. Potential Modulation Speed	> 100 GHz [i]	~ 30 GHz	~ 30 GHz
13. Electrooptic Modulator	Yes[j]	Yes	Yes
14. Waveguide Amplifier	Yes	Yes	Yes
15. Fabrication Cost	Low	High	High

[a] A single-mode channel waveguide operating at $1.31\mu m$

[b] Polymer can be implemented on any large substrate while GaAs- and LiNbO$_3$-based OEICs are limited by the crystal dimension.

[c] A molded optical bus with 45cm in length has been achieved.

[d] Up to 1250 channels/cm on polymer 500 channels/cm on GaAs and 333 channels/cm on LiNbO$_3$ were reported.

[e] Thin film coating.

[f] By definition GaAs- and LiNbO$_3$-OEICs are thick film devices which are difficult to transfer to other substrates.

[g] High index modulation of the same polymeric material allows us to multiplex hundreds of gratings on the same area for 1-to-many fan-out (useful for high-speed clock signal distribution and wavelength division (de)multiplexing applications).

[h] Polymer dielectric constant is controlled by electron oscillation which has very small dispersion from microwave to optical wave.

[i] Small dielectric constant dispersion gives very small walk-off between microwave and optical wave.

[j] Polymer-based traveling-wave EO modulator with 40 GHz bandwidth has been demonstrated.