Design, Fabrication, and Integration of Micro/Nano-scale Optical waveguide Arrays and Devices for Optical Printed Circuit Board (O-PCB) and VLSI Micro/Nano-Photonic Application

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ABSTRACT

We present a review of our work on the micro/nano-scale design, fabrication and integration of optical waveguide arrays and devices for applications in a newly-conceived optical module system that we call “optical printed circuit board” (O-PCBs) and VLSI micro/nano-photonic integrated circuit. The O-PCBs consist of planar circuits and arrays of waveguides and devices of various dimensions and characteristics to perform the functions of transporting, switching, routing and distributing optical signals on flat modular boards. The VLSI micro/nano-photonic integrated circuits perform similar functions on a chip scale. O-PCBs consist of planar circuits and arrays of waveguides and devices of various dimensions and characteristics to perform the functions of transporting, switching, routing and distributing optical signals on flat modular boards. Fundamentally it contrasts with the electrical printed circuit board (E-PCB), which is designed to perform transporting, processing and distributing electrical signals. We have assembled O-PCBs using optical waveguide arrays and circuits made of polymer materials and have examined information handling performances when they are interconnected with the micro-laser arrays, detector arrays and optoelectronic devices. For VLSI nano-scale photonic integration and applications, we designed power splitters and waveguide filters using photonic band-gap crystals and plasmonic waveguide structures. We discuss scientific issues and technological issues concerning the miniaturization, interconnection, and integration of micro/nano-photonic devices and circuits and discuss potential utilities of O-PCBs and VLSI micro/nano-photonics for applications in computers, telecommunication systems, transportation systems, and bio-sensing microsystems.

Key Words: Optical Interconnection, Photonic Integration, Microphotonics, Nanophotonics, Photonic Crystal

1. INTRODUCTION

In our several previous reports, we reported on the concept of what we call “optical printed circuit board” (O-PCB). This was also proposed as a potential platform for VLSI micro/nano-scale photonic integrated circuit

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Integrated Optics: Theory and Applications, edited by Tadeusz Pustelny, Paul V. Lambeck, Christophe Gorecki,
Proc. of SPIE Vol. 5956, 595602, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.614834

system.[1-5] This is to utilize the concept of space division multiplexing (SDM), which is extensively used in VLSI microelectronics, where the transistors and the electron devices are interconnected and integrated on electronic printed circuit boards (E-PCBs). In O-PCBs, too, micro/nano-scale photonic wires and devices are interconnected and integrated on a planar board, ultimately leading to VLSI photonic integration.[1-5] Photonic devices include micro/nano-scale lasers, switches, couplers, detectors, sensors, actuators, modulators, photonic crystals, quantum dots, and related devices. In addition to the concept of time-division-multiplexing (TDM) and the wavelength division multiplexing (WDM), the space division multiplexing (SDM) is to increase the information capacity by way of miniaturization and integration of electronic and photonic devices.

Historically, there has been much effort to increase the information capacity and performance by way of integrated optics, optoelectronic integration, and photonic integration.[6-27] The O-PCBs are introduced to provide a way of utilizing SDM. O-PCBs provide optical wires and circuits in the form of optical waveguides on a planar board or substrate for optical interconnection and integration of the discrete micro/nano-photonic devices.[1-5] The optical waveguides are fabricated out of polymer materials using thermal embossing or UV-embossing. We describe the processes of design, fabrication, and integration of micro/nano-scale polymer optical waveguide devices, circuits, and arrays for O-PCB application and for VLSI micro/nano-photonic application. For VLSI nano-scale photonic integration and applications, we designed power splitters and waveguide filters using photonic band-gap crystals and plasmonic waveguide structures.

2. DESIGN OF AN OPTICAL PRINTED CIRCUIT BOARD

Fig. 1 shows a schematic diagram of a chip-to-chip optical interconnection module on O-PCB, which is designed to serve for high-speed parallel interconnections using 12 channels at 2.5Gb/s or 5Gb/s. The inter-chip module includes electrical-to-optical and optical-to-electrical conversion units and electrical integrated circuits for data processing and is attached to the O-PCB with solder ball with the alignment between the optical waveguide and the electric circuit within 10μm.

The O-PCB boards are prepared on an E-PCB within a rectangular etching region, 70 mm X 10 mm, at the center of E-PCB. The overall planar area of the O-PCB is 200 mm X 80 mm and the thickness of the O-PCB is 2 mm in the un-etched region and 1 mm in the etched region. Previously fabricated waveguide, which utilized a 45 degree mirror for vertical coupling, is inserted (or embedded) into E-PCB and glues with UV-epoxy. Then

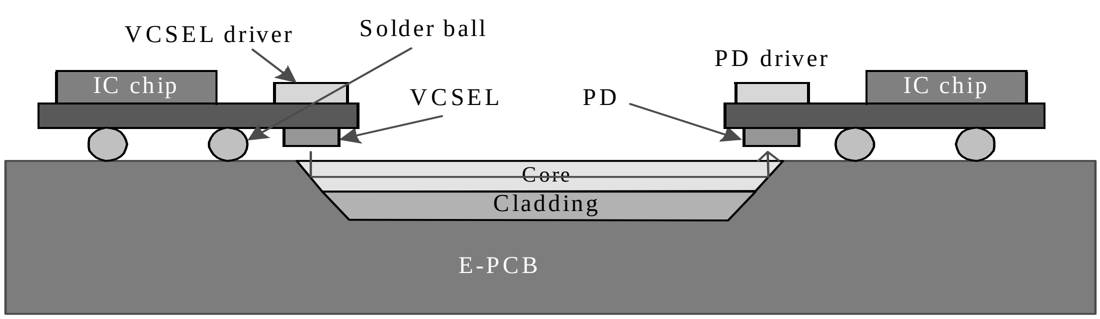

Fig. 1. A schematic diagram of an optical inter-chip connection module

the O-PCB including the embedded waveguides is completed. Chip modules for test are designed and fabricated with conventional analysis of microstrip line. Indium solder balls are placed on the chip modules to bond the O-PCB and chip modules in high precision. Twelve channel multimode polymer waveguides were fabricated by UV embossing technique with a 45˚ silicon mold. The fabricated waveguides have 45˚ slope at the ends of the waveguides and metal film was coated on the surface of the slope for vertical coupling between VCSELs/PDs and waveguides.

When the waveguides are coupled to the VCSELs and PDs vertically, they have a vertical coupling structure at each end of the waveguide. The 45° waveguide mirror uses total internal reflection (TIR). Thermal or UV embossing technique is used for its ease of fabrication process. In order to apply this technique to the optical interconnection technology, the 45° waveguide mold forms a vertical coupling structure with a single fabrication step. We made a twelve channel silicon waveguides mold, which has 45° slope at each end of the waveguide. The cross-sectional size of the waveguide is 50 um x 50 um and the waveguide pitch is 250 um and the length is 7 cm.

3. MINIATURIZATION OF PHOTONIC DEVICES AND REALTED ISSUES

For large scale integration, it is important that photonic devices have to be miniaturized to the smallest possible sizes down to micronscale or nano-scale. Miniaturization entails many scientific and technological issues and challenges. First, in the micro/nanophotonics and integration, the miniaturization entails the proximity effect, the energy confinement effect, the microcavitiy effect in LEDs and microlasers, single photon effect, and the optical interference effect between devices. In microelectronics, the size effect entails the issues of spatial quantization, quantum confinement effect, quantum resonance effect, quantum interference effect, and the image force emerge as important issues. These effects can become important in micro/nano-scale photonics, too, especially, in the devices where the electronics and photonics are integrated together. Nonlinear effects can also become pronounced and the interface physics and environmental issues also become important.

Another important issue in miniaturization is the high field effect. High field within small devices can cause nonlinear interactions. Nonlinear effects can degrade device performances but can also be useful in generating new functional devices. Electron transport through small channels under high field intensity, for example, can induce effects such as velocity overshoot, ballistic transport, hot electron effect, and hot phonon effect. High field and nonlinear effects require special attention when micro/nano-scale photonic devices are integrated with micro/nano-scale electronic devices. Understanding and controlling the dynamics of noises such as quantum optical and chaotic noises in small electronic and photonic devices are also important. Quantum-optical effect, quantum chaotic phenomena, and quantum interference effect will become important aspect of micro/nano-photonics technology.

4. MICRO/NANO-PHOTONICS AND INTERCONNECTION

In the micro/mano-electronic circuits, interconnecting VLSI chips is done with metallic wires. In recent years, there has been increased attention to the use of optical wires, such as optical fibers or waveguides, for optical interconnection for chip-to-chip or board-to-board communication as a way of interconnection. Optical interconnection has made much progress, but the differences and incompatibility between the microelectronics technology and the micro-photonics technology remains as another challenge. Interconnecting micro/nano-photonic chips, circuits, and systems requires approaches that are totally different from that of micro/nano-electronics.

Interconnection in this case can be done very much like optical couplers and connectors in microscale. Optical alignment between micro-scale photonic devices, minimizing inter-connection losses, and maintaining optical modes between devices, are some of the important issues and challenges.

5. MICRO/NANO-PHOTONICS AND INTEGRATION

The miniaturized devices then need to be integrated in small chips or modules for specific missions and functions. Issues related to integration technology are similar to those discussed in relation to the optical interconnection. Some other issues to be addressed in addition should include the design and layout of the devices to be packaged together as a system. Integration of micro/nano-photonic devices can be divided into several categories. First, depending on the type of structure, it can be divided into monolithic integration or hybrid integration. Next, depending on the kinds of devices to be integrated, it can be divided into homogeneous integration or heterogeneous integration. These include: (1) integration of same kind of photonic devices, (2) integration of two different kinds of devices, and (3) integration of several or many different kinds of photonic devices. Integration between the micro/nano-electronic devices and photonic devices is also a formidable challenge.

6. MICRO/NANO-PHOTONIC MATERIALS

There have been many different kinds of materials that have been used for micro/nano-photonics. These materials include semiconductors, inorganic materials, and polymer/organic materials. Semiconductors are extensively used for active devices like lasers, detectors, and modulators. Inorganic materials have been explored for novel nonlinear functions. Newly emerging materials are organic or polymeric materials. Polymer organic materials are used for both active functions and passive functions including waveguides, light emission, switching, modulation, memory, and display. The merits of polymeric materials for these functions are: (1) high electro-optic coefficient and nonlinearity, (2) good dielectric properties, (3) temperature stability (4) chemical and mechanical stability, (5) compatibility with semiconductor fabrication technologies, (6) lower production costs, (7) possibility of implementing complex, high- density interconnect routing structures, and (8) compatibility with board-level electronic packaging. There are two different kinds of materials in polymers, depending on their properties. In the photo-refractive polymers, used especially for applications in optical memory system, improvements are needed in access time, reproducibility, low degradation, thermal endurance, the long-time dark storage, minimum background scattering, thick sample synthesis, and asymmetric writing and reading processes. In the photopolymer type materials, the merits include high diffraction efficiency, low cost, ease of handling, and simple production over the photo-refractive materials, inorganic materials or semiconductor materials. Possibility of producing micro/nano-sturctures using embossing or imprinting techniques is another strong advantage of polymer materials.

7. SYNTHESIS OF POLYMERIC MATERIALS

We purchase most of the polymer materials for our use but for some specific applications we synthesize our own polymer materials. In recent years, block copolymers have received much scientific and technological attention due to their ability to self-assemble into a series of periodic ordered microstructures *via* microphase separation between the constituent block segments. There are a number of applications by using their phase-separated morphology both in the solid state and in solutions. Recently, atom transfer radical polymerization(ATRP) has been used in such a manner to build block copolymers of radically polymerizable monomers.[28-29] In this process, active halogens are incorporated at the chain ends of polymers to form macroinitiators.[30] Such macroinitiator have been used to extend to synthesize block and graft copolymers. In our studies, we synthesized a novel diblock copolymer of polypentafluorostyrene-*block*-poly(methyl methacrylate) (PPFS-*b*-PMMA) by ATRP technique. The PPFS-*b*-PMMA diblock copolymer are synthesized by ATRP in the bulk state. The synthetic procedure is similar to the preparation of PPFS macroinitiator. PPFS-Br (0.33g, 9.7×10^{-5}mol) as an initiator is added to a round-bottom flask, equipped with a magnetic stir bar. CuBr (0.015g, 9.7×10^{-5}mol), PMDETA (0.02g, 9.7×10^{-5}mol) and MMA (3.9g, 39mmol) were added in the solution. Then the mixture was purged with N_2 and stirred for additional 3 hr**.** The synthesis of a PPFS-*b*-PMMA diblock copolymer consists of two steps: That is, the syntheses of PPFS-Br macroinitiator and PPFS-*b*-PMMA diblock copolymer. The ^{1}H NMR spectrum of the block copolymer allows the molar composition to be determined from the relative intensity at 1.7-3.0 ppm ($–CH–CH_2–$ of PPFS) and 3.5-3.8 ppm ($-OCH_3$ of PMMA).[31]

8. FABRICATION OF POLYMER WAVEGUIDES AND CIRCUITS

O-PCB is used as a planar board to integrate photonic devices using polymer-based optical waveguides as interconnecting optical wires. For embossing, we design and fabricate a twelve channel waveguide silicon mold. Devices that we designed and fabricated include arrayed waveguide grating (AWG) devices, directional couplers, multimode interference (MMI) devices, micro-ring/micro-racetrack devices, and photonic crystal devices as micro/nano-photonic devices.[32-41]

To fabricate waveguide circuits and devices by embossing or imprinting technique, we first have to fabricate mold. To fabricate a twelve-channel silicon waveguide mold, we etched silicon with KOH and KOH saturated isopropanol solutions to make vertical and 45° slope sidewalls. The fabrication procedure is as follows. First, (1) a metal mask is patterned on a silicon substrate. Then, (2) the silicon is etched with KOH to form waveguide pattern. Next, (3) SiO_2 is grown over the silicon substrate. (4) the metal mask is stripped and photoresist is patterned on the ends of the waveguide structure. Next, (5) SiO_2 is grown. Next, (6) photoresist is stripped. Next, (7) the ends of the waveguides are etched with KOH saturated with isopropanol solution to form 45° slope. Finally, (8) SiO_2 is stripped and the 45°-ended waveguide silicon mold is completed. These molds are then used as the basis for embossing optical waveguides and wires.

The waveguide fabrication process is as follows. First, UV curable polymer is dropped in the cavity of a transparent substrate. Then, silicon mold is pressed and UV source is irradiated. Next, silicon mold is detached and metal film is coated. Next, polymer is dropped for core formation. Next, a flat substrate is pressed and UV source is irradiated once again. Finally, upper and lower substrates are detached. The 45° slope at the end of each waveguide is fabricated in two ways: (1) Cutting the end at a 45° slope or (2) concurrent formation of the 45° slope with the formation of the waveguide. Sometimes, the 45° mirrors are fabricated in a curved shape to enhance the coupling efficiency, as discussed below.

9. FABRICATION OF CURVED MIRRORS FOR VERTICAL INTERCONNECTION

In order to increase the coupling efficiency and to provide means for low-cost fabrication of waveguides for vertical interconnection, we sometimes designed and fabricated a silicon master for a curved mirror that can be fabricated by low-cost, high-volume embossing of low-cost polymers. The interconnection is made for the electrical printed circuit board (E-PCB) and the optical printed circuit board (O-PCB) using three different types of mirrors formed at the end of each waveguide. The interconnection efficiency for curved mirror types is superior to other types. The patented simple fabrication procedure provides good curved structure. The results of these mirrors will be reported somewhere else.

10. ASSEMBLY AND TEST OF O-PCB

The above micro/nano-scale components and waveguide circuits are then assembled together to construct an O-PCB. Optical waveguide circuit arrays are used for interconnection between light sources and detectors. Arrays of vertical cavity surface emitting lasers (VCSELs) and photodiodes (PDs) are wire-bonded or flip-chip bonded to the silicon devices for optical input–output (I/O) interconnection. Spacers of indium solder balls in diameters of about 250 micron were used to bond the VCSEL-carrying blocks, the PD-carrying blocks, the O-PCBs and the E-PCBs. The alignment between the waveguide and the electric circuit passively lies within 10µm error. To assemble an O-PCB, an array of polymer waveguides with 100X100 micron core and a pitch of 250 microns were fabricated by UV embossing with 45° mirrors. The lightwave beams from the VCSELs are reflected 90° and are coupled into the waveguides in the O-PCBs. The lightwaves through the waveguide are then again reflected into the detectors via 45° mirrors. The total length from one end of the waveguide to the other end is 70mm and the refractive index of the waveguide is 1.475 at 850nm.

The O-PCB is put together with an electrical printed circuit board (E-PCB) carrying the electrical circuits such as data distribution circuits, clock distribution circuits, and/or the driving circuits for micro-lasers and micro-detectors. The bonding of the E-PCBs and the O-PCBs is done with the difficulty associated with the optical alignment, planarity, thermal mismatch, and mechanical mismatch in mind. In order for the E-PCBs to align accurately with the O-PCB, a number of solder ball sites were added. The fabricated prototype shows data rates up to 10 Gbp/s. The integration can offer not only an enhanced data transmission rate but also clock synchronization for high performance and high-speed CMOS digital systems. Optically distributed clocks have less clock skews and jitter, thereby allowing this idea for optical on-chip clock distribution and optical on-chip interconnection.

11. AN EXAMPLE OF O-PCB

As an example of an O-PCB, we designed and fabricated a newly conceived optical switching device, which we call "depleted optical thyristor". It is an optical switching device, which can be used for optical self-routing and optical neural network.[42] The optical thyristor uses an optical input signal as gate current, which takes part of current injection to the center layer of the general thyristor. The optical input signal is absorbed in the depletion region of center layer, and it reduces the switching voltage with generating photo-current.[43,44] The vertically injected depleted optical thyristor has potential applications in advanced optical interconnection systems such as optical printed circuit board and inter-chip interconnection. In optical interconnection systems, the vertically injected depleted optical thyristor can be used as a fundamental packet-switching device with both logical and relational functions.[45]

Figure 2 schematically illustrates the structure of the vertically injected depleted optical thyristor. The device has a ridge-type laser structure buried in polymide layers. We found that the device did lase at the wavelength of 1.55 um. The measured switching voltage and current are 3.36 V and 10 uA. The lasing threshold current is 131 mA at 25 °C. In optical interconnection systems, the arrays can be inserted in the polymer waveguide on the optical PCB. The optical signal through the polymer waveguide is injected to the vertically injected depleted optical thyristor and its output signal can be controlled by the vertically injected optical control signal.

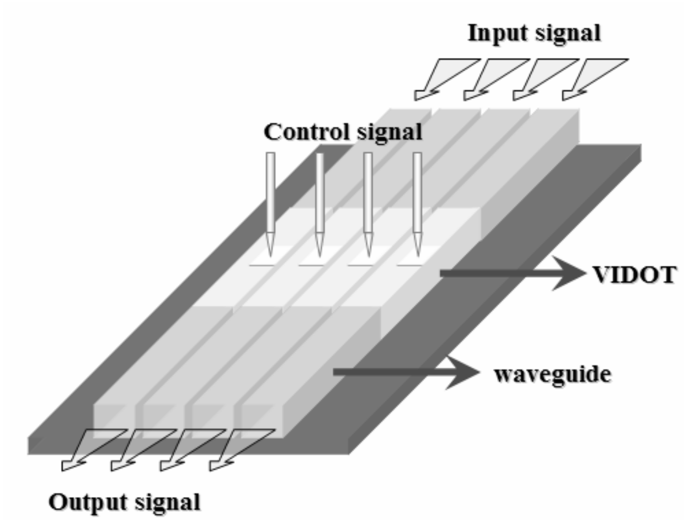

Fig. 2. Example of a vertically injected depleted optical thyristor on an optical printed circuit board

12. NANO-SCALE PHOTONIC CRYSTAL DEVICES FOR VLSI APPLICATIONS

In order to realize VLSI optical circuits, we have used photonic crystals to design and fabricate power-splitting devices and wavelength-splitting devices based on directional coupler structures. We call it a "chop-stick" structure and have found it superior to other structures, such as Y-junction, in the formation of high-density VLSI nano-photonic circuits. The photonic crystal structure that we used is a triangular array of air-holes perforated in GaAs. The details of the structure and the power-splitting mechanism are reported in an earlier report [46] Using a similar photonic crystal structure, we also designed a multimode interference (MMI)-like structure using a 2-dimensional photonic crystal. We also found it highly effective for wavelength splitting in different directions. We also designed a bandpass filter by using waveguide bending in a 2-dimensional photonic crystal.[47] We used a triangular lattice structure of air holes etched in a dielectric substrate. We examined the dispersion characteristics of the single-line-defect waveguide to find a new way of designing a bandpass filter. We also examined the coupling efficiency of lightwave between a micro-scale waveguide and a nano-scale waveguide using the models of mode adaptation that we have developed for micro-scale waveguides.

13. NANO-SCALE PLASMONIC DEVICES FOR VLSI APPLICATIONS

Another example of achieving nano-scale photonic devices is the use of plasmonic waves along the interface between a dielectric material and metal stripe waveguides.[48-59] We investigated on the integrated optical devices and circuits based on surface plasmon polaritons (SPPs). One area of potential application of SPPs is in devices based on metallic waveguides of finite width at telecommunication wavelengths. Such waveguide consist of a thin metal film of finite width surrounded by a dielectric material. SPPs are electromagnetic modes constituted by a light field coupled to a collection election oscillation propagating along an interface between two media with real parts of permittivity of opposite sings, usually metal and a dielectric interface. For sufficiently thin metal film (several tens of nm) surrounded by dielectric, the SPPs associated with the upper and lower of the metal-dielectric interfaces couple and form an symmetric mode, a long range SPP (LRSPP), whose propagation length increases dramatically with decrease of metal thickness. LRSPP mode supported by a thin and narrow metal stripe surrounded by dielectric can propagates cm order. Compared with conventional dielectric waveguides, metal stripe waveguides have inherent loss caused by metal and show different field distributions in waveguide. For a sufficiently thin metal film embedded in dielectric, the propagation loss decreases under 1dB/cm with the decrease of the film thickness. The field distribution of metal stripe waveguide extends several micron meters from the metal stripe and can be adjusted close to that of a single mode fiber by varying the stripe thickness and width. Furthermore, such a stripe can also be used to carry electrical signals affecting the LRSPP mode. And the metal stripe waveguides (MWGs) are good candidate for 3D structured optical integrated circuits because the fabrication of the MWGs do not need additional etching or wafer boding process compared conventional dielectric based waveguides.

We have designed and fabricated vertical directional couplers consisting of metal stripe waveguide embedded in polymer. We then compared the coupling characteristics of vertical and later directional couplers. The coupling length of the fabricated vertical directional coupler consisting of 20nm thin and 5um wide gold stripes is estimated as 260um and it shows reasonably good agreement with the calculated value. The devices show high extinction ration of about 28dB. In order to increase the density of optical integrated circuits we constructed multi-layer, three-dimensional optical circuits. To send and receive optical signal between multi-layered optical integrated circuits, vertically operating coupler and switch were constructed. Here we report on vertical directional couplers, which consist of metal stripe waveguides operating at the telecommunication wavelengths. We also analyzed the properties of the lateral directional couplers and the vertical directional couplers.

14. APPLICATION OF O-PCB AND MICRO/NANO-PHOTONIC DEVICES

General Systems. In the application of the O-PCBs and the VLSI photonics, we can expect many new functions in the form of modules. They can also complement or even replace many different kinds of electrical PCBs (E-PCBs) being used in various applications because of their superior characteristics over the E-PCBs. The advantages of the O-PCB include the wide bandwidth, light-weight, low power consumption, and the avoidance of the electromagnetic interference (EMI). The technology for the O-PCB will be improved to integrate various photonic components on massively producible lightwave boards. E-PCBs can be found nearly everywhere for electronics systems. Thus, the future application areas of the O-PCBs can become as common as those of the E-PCBs used in the age of electronics.

Telecommunication Systems. Photonics is already a well-established technology in telecommunication, but the question that follows is the utility of O-PCBs and micro/nano-photonic integrated circuits for telecommunication applications. The most important issue in telecommunication is the ultimate transmission capacity that it can attain. This may be achieved basically through the maximum use of time division multiplexing (TDM), wavelength division multiplexing (WDM), and space division multiplexing (SDM). TDM and WDM critically depend on the dispersion, fiber length, signal power, channel separation, and the total channel number. SDM requires miniaturization and high-density integration of devices. The transport capacity is also fundamentally dictated by the uncertainty principle of the temporal and spectral origin. The uncertainty principle, $\Delta t \times \Delta \nu > 1/2$, limits the simultaneous use of high-speed TDM and high-density WDM signal processing, where Δt and $\Delta \nu$ represent temporal and spectral width the optical communication signal. In our study the maximum obtainable bit rate was about 2.3 Tera bit/s with the combined TDM and WDM for relatively long pulses. This limit, however, may be further extended by the SDM. This is where the utility of optical printed circuit board can find a value. Another issue is the reduction of the cost for the subscribers. In the subscriber network, for example, the demand for the fiber-to-the-home (FTTH) network is rising and a low cost solution for the optical components of optical subscriber networks is necessary to make the networks economically viable and competitive. One way to reduce the price of optical transceiver modules for the subscriber networks is the use of optically integrated devices. The massively producible embossing technology used for the polymer-based photonic integrated waveguide devices of the O-PCBs can be applied for fabrication of low cost optically integrated device.

Computer Systems. In the current computer technology, the clock speed of the computer processor chips can go well over 3 GHz, but the speed of the data traveling along the bus lines still remains much below 1 GHz range. In view of the fact that the transmission lines in the network need several Gbit/s on the basis of current fiber-optics technologies, there is expected a significant data transmission delay between the processor chips and the data ports. Compared with electrical transmission lines, the speed of the O-PCB can easily reach several Gbit/s or GHz for data and clock lines to help for board-to-board interconnection, chip-to-chip interconnection, and for intra-chip interconnection.

Switching Systems. Use of optical switching is an attractive concept for high capacity optical interconnection and computing. The inherent properties of optics for parallel processing are especially suitable for these ideas. The unique properties of photons that make them useful for switching include: the high bandwidth, week interaction between light beams, and strong interaction between light and matter. Switching systems can be configured either in two-dimensional structures (like planar-type waveguide switches) or in three-dimensional structures (like free-space interconnection switching or MEMS switching). In two-dimensional configurations, Mach-Zehnder type waveguide devices and polarization dependent devices such as polarization separator, polarization selector, and polarization controller are electro-optic devices. As the need for high volume processing rises, there have been increased efforts to make the size of individual devices small and increase the density of integration. This can be realized by the use of space division multiplexing (SDM) and this is where the value of O-PCB for photonic switching comes in. A number of electro-optic or semiconductor based space-division multiplexed switching schemes combined with time-division multiplexed signals have been investigated. The major advantages of the planar integrated optics can allow increased signal transfer speeds of each channel and parallel signal processing between a number of channels.

Sensing Systems. In order to make devices and systems smart, intelligent, and human-friendly, optical and photonic sensing is becoming increasingly important. The object of sensing includes: motions, images, sounds, temperatures, pressures, vibrations, chemical variations, and others. Optical fibers are extensively used for sensing structural variations and distortions in buildings, bridges, transport systems, and other structures. Anti-crime sensing and recording are also becoming popular along with the systems for automation in homes, offices, and factories. Photonics is a critically important tool in sensing and collecting information. In recent years, as the MEMS and NEMS technologies have attracted much attention and as the devices become small and as the need for integrating various devices of diverse functions rises, the need for integration and interconnection for MEMS and NEMS increases. This is where the role of O-PCB can be increased.

Transportation Systems. Some of the most outstanding advantages of O-PCB is the high speed, compactness, light-weight, low-energy consumption, wearable and portable. These advantages are especially suitable for transportation systems. In recent years, there has been increased effort to utilize the optical fiber networks in automobiles and avionics for intelligent vehicle systems as well as for various multimedia entertainments and safety control systems. In the past several years some automobile companies have started to replace the electric wires with plastic optical fibers for interconnection of information and entertainment devices within passenger compartment. A standard for the media-oriented system transport (MOST) has been introduced in the automotive industry and already planar bi-directional transceivers are being investigated for applications in the form of flat optical printed circuit boards in the automobile networks. Planar optical flat printed circuits in the form of modules can thus be good application examples of the O-PCB technology. O-PCBs can be used also for avionic systems and flying systems, including satellite systems.

15. SUMMARY AND CONCLUSION

We presented an overview on the recent progresses of our study on the design, fabrication and integration of micro/nano-scale polymer optical waveguide arrays and circuits for optical printed circuit board (O-PCB) and VLSI micro/nano-photonic applications. We first examined the scientific and technological issues concerning the miniaturization, interconnection and integration of micro/nano-scale photonic and electronic devices. We designed and fabricated micron-scale polymer-based waveguide circuits and arrays using thermal embossing and UV embossing techniques. We reported detailed procedures of fabricating molds and performing embossing. We designed and constructed arrayed waveguide grating structures, directional couplers, multimode interference devices, microlenses, curved 45-degree vertical couplers for various functional devices. We designed and constructed an O-PCB and integrated it with an E-PCB for inter-chip interconnection. For VLSI applications, we designed directional couplers, multimode interference devices, and wavelength filters for power splitting application and wavelength splitting application using 2-dimensional photonic crystals. We investigated on the plasmonic phenomenon and its application for the fabrication of directional couplers and other waveguide devices in nano-scale. We have examined the physical and optical characteristics of waveguide devices, circuits and arrays and have examined the system characterization and the information transmission properties of the assembled O-PCBs. We measured the information transmission capacities up to 2.5 Gbps and 10 Gbps. We also discussed the considerations for the use of O-PCB and VLSI micro/nano-photonic integrated circuits for applications in telecommunication systems, computer systems, sensing systems, and transportation systems.

ACKNOWLEDGEMENTS

This work has been supported by the Korea Science and Engineering Foundation (KOSEF) through the Grant for the Integrated Photonics Technology Research Center (R11-2003-022) at the Optics and Photonics Elite Research Academy (OPERA), Inha University, Incheon, South Korea. The authors acknowledge H. S. Lee, H. S. Bae, S. M. Ahn, S. H. Park, C. H. Choi, M. W. Lee, D. K. Kim, Y. Kim, S. B. Jo, all in the OPERA center, for their invaluable assistance in this research and in preparation of this manuscript.

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