Polymer optical waveguide based bi-directional optical bus architecture for high speed optical backplane

Xiaohui Lin[a], Xinyuan Dou[a], Alan X. Wang[b] and Ray T. Chen[1,*], Fellow, IEEE

[a] Department of Electrical and Computer Engineering, the University of Texas at Austin, Austin, TX, 78758, USA

[b] School of Electrical Engineering & Computer Science, Oregon State University, Corvallis, OR, 97331, USA

ABSTRACT

With the technology trend of using optical interconnects as an alternative to traditional copper interconnects, basic elements such as waveguides and waveguide bus structure are studied worldwide. A novel 3-node bi-directional 50µm optical waveguide bus architecture with embedded mirrors is proposed and fabricated on flexible substrate. The fabrication is achieved by lithography-free molding. Different from other replicating methods, the mold demonstrated here is a nickel metal mold achieved by low cost electroplating and can be used repeatedly. The data transmission test up to 10Gbps using vertical cavity surface emitting laser (VCSEL) has been performed to evaluate the device. The results show that the device is capable of emitting and receiving high speed data. Thus it can serve as a high performance optical backplane. Such mold fabrication technology can also be applied to smaller features size structure. The molds of 5µm wide waveguides and photonic crystal waveguide structures with 250nm hole size are fabricated and the molded structure profiles are shown.

Keywords: optical waveguide, bus architecture, SU8 pre-mold, electroplated nickel mold, polymer molding

1. INTRODUCTION

Multimedia information is penetrating into almost every aspects of our daily life. From high speed internet to 3G, 4G LTE network, from internet TV to cloud storage, people are raising higher demands for audio/video streaming, than traditional radio or broadcasting services. In this digital era, all these demands should be supported by high speed, wide bandwidth data transmission technology. Traditional copper interconnect technology is facing great challenges when high bandwidth is required. Alternatively, optical interconnects is drawing researchers' attention due to its intrinsic advantages such as immunity to magnetic interference, high speed operation and low power assumption, etc[1]. Chen etc[2]. have compared the optical interconnects in detail with traditional copper interconnects in many aspects including delay uncertainty, latency, power, and bandwidth density etc. However, it is currently impossible to use optical interconnects to completely replace traditional copper interconnect. Currently, as illustrated in Figure 1[3], we are still in transition edge of the copper interconnect. It is reasonable to integrate the optical channels into the current electrical components to achieve high speed data transmission in the "bottle neck" of an application. Therefore, the connection can be rack-to-rack, board-to-board or sandwiched among copper interconnects. The most widely studied element in optical interconnects is optical waveguides. Several parallel waveguides form a waveguide array which features huge bandwidth by sending signals at the same time. Also, waveguides can form numerous pairs of point-to-point communication and it is useful when combining with electrical switch backplanes. However, due to the topological limits, each data transmission requires an initial of routing overhead. Thus the lack of any broadcasting function makes it difficult to minimize the overall interconnect latency and produce a lot of waste. To overcome these difficulties, optical bus architectures need to be replaced with broadcasting feature in the backplane, instead of just simple point-to-point connection structure. Many optical interconnects schemes have been proposed and investigated, including free space[4], embedded fiber connection[5], and optical slots[6]. However, a fully embedded board-level optical interconnect with reduced packaging difficulty is still needed. Here, we demonstrate an architecture of the fully embedded optical layer

* Ray T. Chen: chen@ece.utexas.edu

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shown in Figure 2, where the optical interconnect layer is sandwiched in copper interconnects and it includes an embedded VCSEL array, a photodiode array, and a polymeric channel waveguide array with 45^o mirrors. The driving electrical signals to modulate the VCSELs and the demodulated signals received at the photodiode flow through electrical vias. The fully embedded structure makes the insertion of optoelectronic components into microelectronic systems much more realistic. The actually optical bus demonstrated in this paper is a novel bi-directional optical bus architecture with 3 fully functioning nodes and featuring vertical coupling via embedded mirror. This structure has the advantages of enhanced bandwidth, increased reliability, package compatibility and significantly lower fabrication cost.

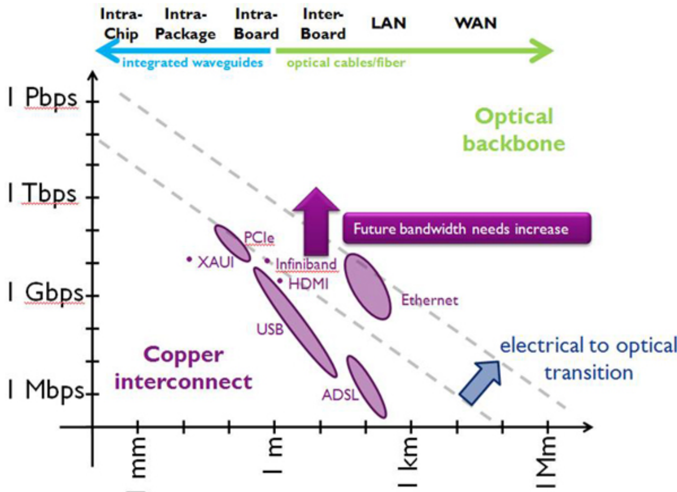


Figure 1 Bandwidth by Distance applications requirements for short distance communication links[3].

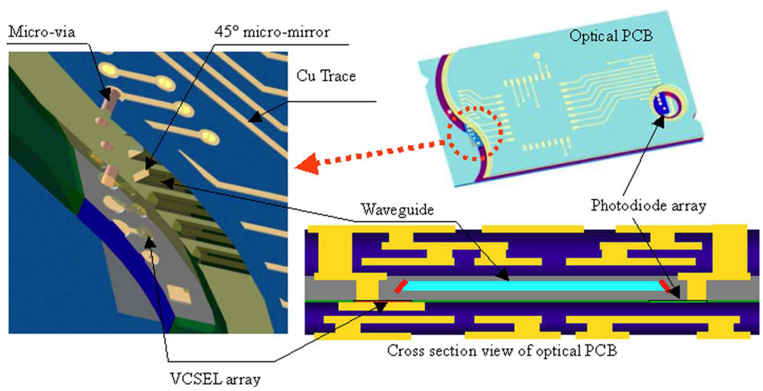


Figure 2 Illustration of the fully embedded optical interconnect architecture.

2. BUS ARCHITECTURE DESIGN

The bus structure design and main dimensions are shown in Figure 3. It has 4 main elements: (1) node formed with a pair of laser diode (LD) and detector (D) as shown in Figure 4(a). Each node is able to send/receive signals to/from all other nodes at the same time, maximizing the efficiency of data transmission by broadcasting method; (2) Embedded mirrors with 45^o slope as shown in Figure 4(b). It enables light coupling into and out of the bus vertically using VCSELs; (3) ratio Y-splitter with engineered width ratio as shown in Figure 4(c) and (d). By adjusting the width ratio of each branch, the light splitter ratio can be tuned. (4) Parallel main optical bus waveguide. The two main buses can transmit optical signals along two opposite directions. Take the central node for example of how the bus work: The optical signals from the laser diode (LD) of each node will be split into two beams and transmitted bi-directionally into the two bus waveguides through two unidirectional branch waveguides. The detector (D) of each node is also capable of receiving optical signals from both of the two bus waveguides, benefited from the two unidirectional branch waveguides that are connected with them. The two parallel optical bus waveguides in conjunction with the unidirectional branch waveguides ensure completely non-blocking interconnection among any existing node without any wiring crossing. The LD and D can be located either on the associated cardboards or the optical backplane itself. In this case, a 45° embedded micro-mirrors are used to reflect surface normal optical signals from modulated VCSELs into the waveguide plane. The waveguide materials are polymers which has low propagation loss at 850nm. The entire device is built on flexible substrate which is bendable to accommodate different application environments.

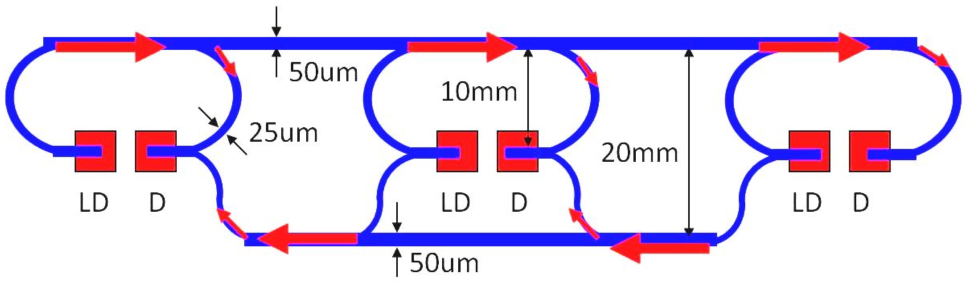
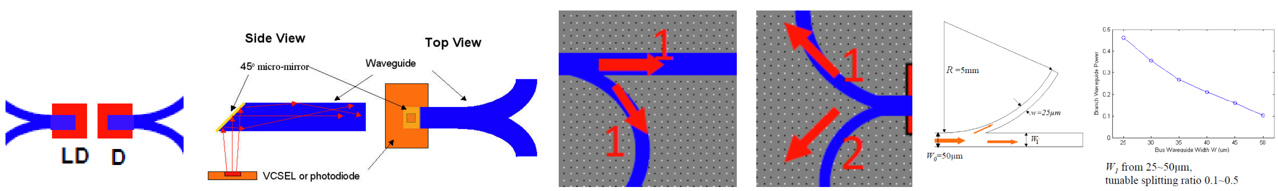


Figure 3 three-node bi-directional optical bus structure



(a) (b) (c) (d)

Figure 4 main components in the bus structure (a) node (b) ratio splitter (c) splitter design (d) embedded mirror

3. DEVICE FABRICATION

Typically, making polymer waveguide use conventional semiconductor fabrication process which is photo-lithography based technology. Such process should inevitably include the plasma etching step to etch the polymer using photo resist as mask. However, high energy plasma will cause permanent damage to the surface of polymer and make it rough and eventually results in high scattering loss during light propagation. In addition, the process is not suitable for mass production. In the presented work, we employed a molding method which uses nickel as a mold to shape the polymer material. The advantage is that such process avoids the plasmas etching step thus renders smooth surface. Although the mold fabrication process is complicated, once done, the mold can be used several times and it will greatly reduce the entire processing time and cost. Additionally, special feature such as 45^{o} slope is hard to fabrication using etching method but achievable using molding method.

The fabrication process for this work can be summarized into 4 main steps as illustrated in Figure 5. It includes SU8 pre-mold fabrication, nickel metal mold by electroplating, molding process and final device fabrication. The 1st step is making SU8 pre-mold. The pre-mold is used as a template for the nickel hard mold and its fabrication quality is of great importance to all the following steps. The slope is fabricated using tilted exposure in water. UV light shines into SU-8 with a specific angle to form 45^{o} slope. The hard nickel mold is prepared in the 2nd step by electroplating desired thickness into the SU8 pattern, on pre-buried gold seed layer. The plating time, current density and stability during the plating should be carefully controlled to ensure good profile and smooth surfaces. In the 3rd step, After SU8 removal, the nickel mold is used to mold the bottom cladding polymer that is spin-coated on a flexible device substrate. After UV curing of the polymer, the mold is detached from the device substrate. Here, a thin layer of resist is pre-applied in between the mold and device, serving as release agent. Following that, on the 4th step, gold is deposited on the 45^{o} slope region to enhance the mirror reflectivity. The waveguide is finalized by coating the channels with core layer and top cladding layer, with proper UV curing. In the following part, we will describe in detail about these four steps.

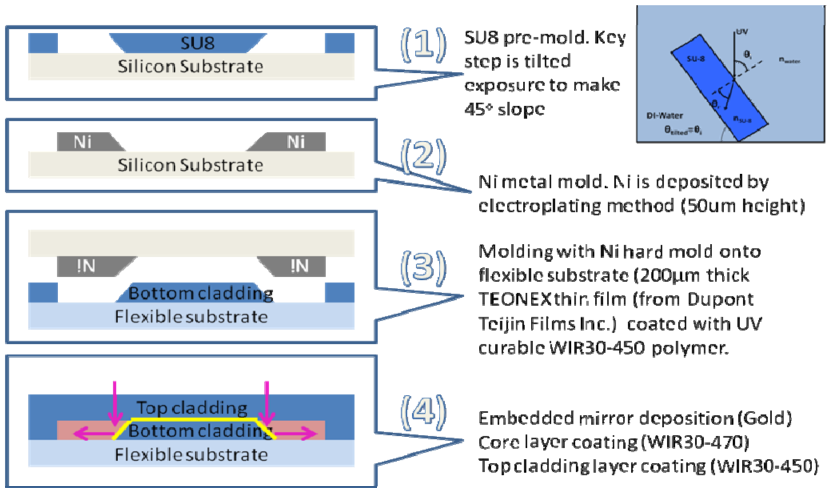


Figure 5 main fabrication steps for the optical bus architecture

3.1 SU8 pre-mold fabrication

The schematic process to prepare the optical bus pre-mold is shown in Figure 6. First, a layer of 50µm thick SU-8 is spin-coated onto silicon substrate which has a 5nm/50nm Ti/Au seed layer coated. After properly pre-baking the SU8 resist, one traditional exposure and two tilted exposures are performed in order to achieve the bus waveguide pattern and the reversed 45° slope surfaces. The first exposure is carried out through vertical exposure to create the bus structure using the optical bus mask. The second and third exposures are carried out tilted under DI-Water to achieve 45° surfaces at the input and output node ends of the bus structure. In this way, the incident UV light goes into the SU8 with 45° to the sample surface. Exposing in water can reduce the incident angle to minimize the UV intensity loss due to surface reflection. Detailed description of tilted exposure can be found in previous papers[7, 8]. After the three exposures, post-exposure bake and developing are carried out to achieve a SU-8 based optical bus waveguide pre-mold. Figure 6 also shows the SEM images of the Y-splitter and 45° slopes from the SU-8 pre-mold.

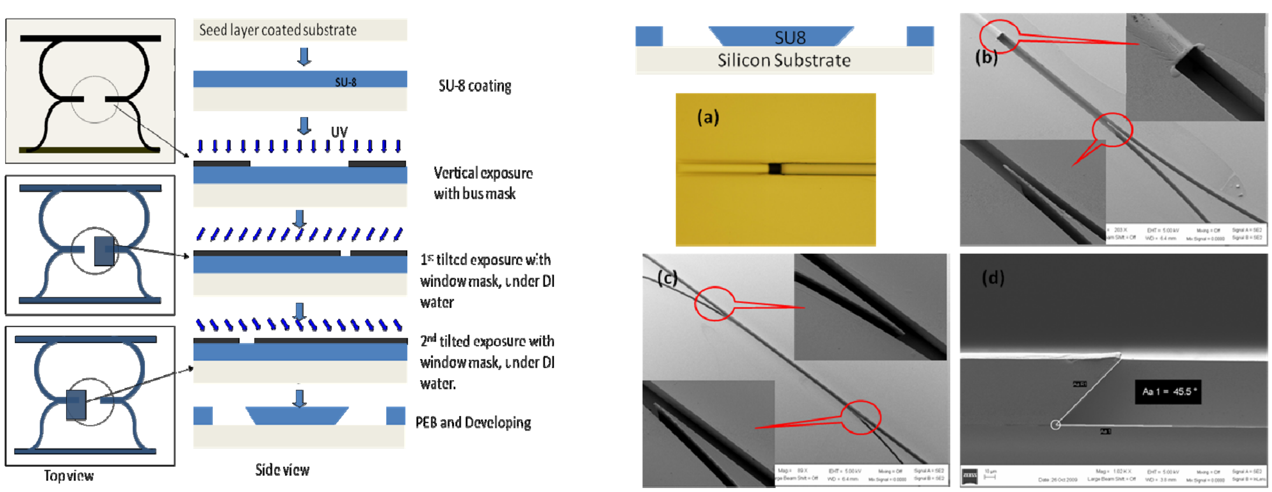


Figure 6 illustration of SU-8 pre-mold fabrication process and SEM pictures of achieved pre-mold

3.2 Ni metal mold utilizing electroplating method

Nickel deposition is achieved by electroplating. Compared to evaporation/lift-off method, electroplating is featured by its high deposition rate. For thickness of 50µm, it is almost impossible to achieve by other deposition methods. The Ni electroplating kit is commercially available from Caswell Inc. The pre-buried Ti/Au layer is served as seed layer for electroplating. It is critical to maintain a very small plating current density (1-2mA/cm^2) at the starting stage of electroplating in order to achieve a strong adhesion between the Ni mold and the seed layer. Larger current density

(10mA/cm2) is used in the middle stage of the process to ensure constant deposition of nickel film. At the end of plating process, small current density (1-2mA/cm^2) is applied to give the nickel a shiny finish. The plating speed is around 120nm/min at 10mA/cm^2. To achieve 50um of thickness, the typical plating time is around 6-7hrs. After the required thickness of nickel is acquired, SU-8 resist is removed by Remover PG to release the nickel mold. Figure 7 shows the SEM images of each node and the slope feature. Mold fabricated out by this method is featured by its smooth surface, good adhesion to substrate and reusability.

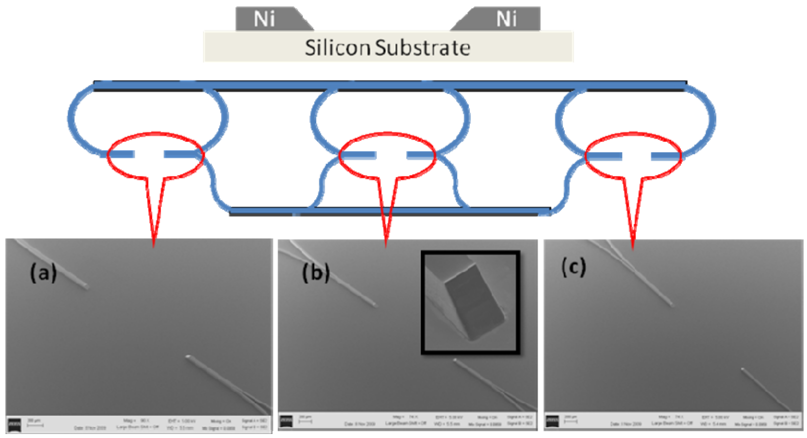


Figure 7 Electroplating nickel into SU-8 pre-mold to make nickel metal mold.
SEM pictures show the 45o slopes from each node.

3.3 Molding process

A flexible TEONEX thin film (from DuPont Teijin Films Inc.) with thickness of 200um is used as the substrate. First, ZAP-1020 is spin-coated and baked as the adhesion promoter onto the substrate. Then the bottom cladding material WIR30-450 (n=1.45@850nm) from ChemOptics is spin-coated onto the substrate and UV cured. Following that, AZ5209 photo resist is spin-coated on nickel hard mold as the release layer. A small amount of cladding material is dispensed on the nickel mold and brought into contact with the bottom cladding material coated substrate. Extreme carefulness should be applied to make sure all the air bubbles are removed in-between the interfaces. External pressure is applied to keep the mold and device in good contact. The UV cure is performed to harden the polymer. After UV cure, the de-molding process is finished in acetone which dissolved the photo resist in-between the mold and device. The SEM pictures of the molded waveguide bus is shown in Figure 8.

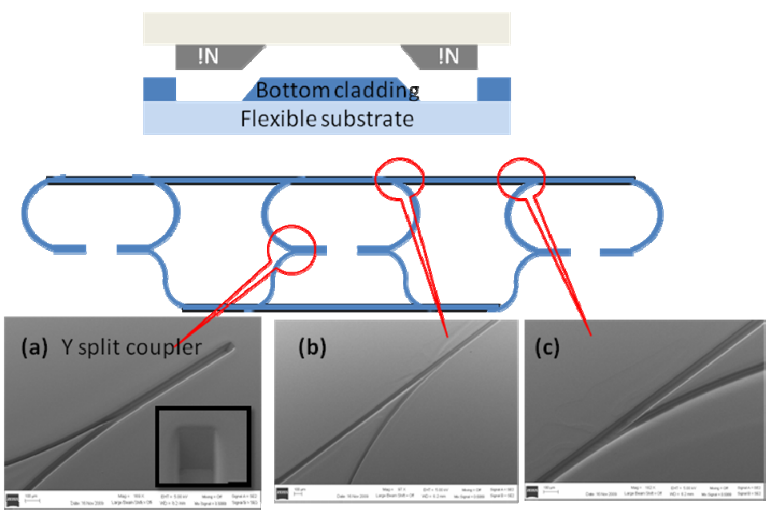


Figure 8 Molding waveguides using nickel metal mod

3.4 Embedded mirror coating and device finalization

After successfully peeling off from the substrate, the waveguide device is coated with 200nm of Au by e-beam evaporation method. Gold coating helps to enhance the reflectivity of the slope thus increase the coupling efficiency. Then the Au film outside the 45° mirror region is removed by wet etch method. After that, the imprinted trenches are filled with core material WIR30-470 (n=1.47@850nm), and UV cured for 12min. At last, top cladding it spin-coated and UV cured. In this way, this polymeric bus waveguide device is finally successfully fabricated. This process is illustrated in Figure 9 which also shows a picture of the actual device. The flexible substrate is placed on a glass slide in order to easy handling when performing optical test.

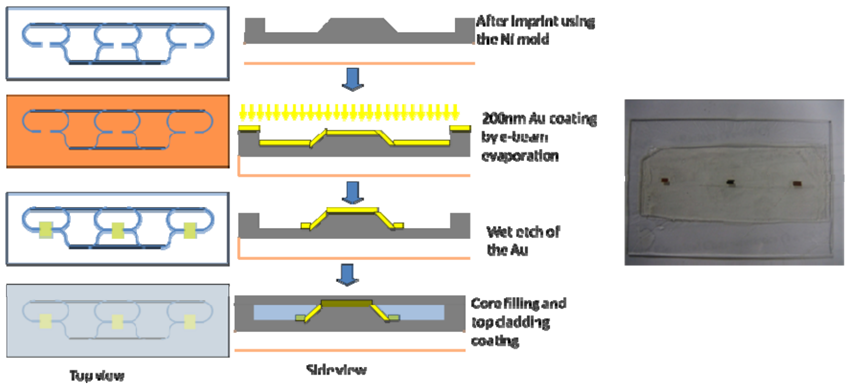


Figure 9 Device finalized: gold coating, core filling and top cladding filling. Actual device is shown on the right.

4. DEVICE EVALUATION

The device evaluation includes insertion loss test and high speed data transfer test. As shown in Figure 10(a), in order to achieve best coupling, we first use a red laser at 635nm to observe the output of the optical bus waveguide through microscope. A single mode fiber is fixed above the 45° micro-mirror region of the input node. Inset image in Figure 10(a) is the optical output pattern on the monitor through microscope. After confirming each route for the optical bus waveguide works, the laser source is switched to 850nm wavelength to measure the output signal. An 850nm laser diode with a 9/125μm single mode fiber (SMF) pigtail is normally coupled into the bus waveguide input node through the 45° micro-mirror. The output power at the output nodes is measured by a photo detector fixed just above the bus waveguide output nodes. The minimum insertion loss we can achieve is around 15dB. Comparing to the straight waveguide, the relatively high loss is contributed by the curved structure of the bus waveguide and the power splitting.

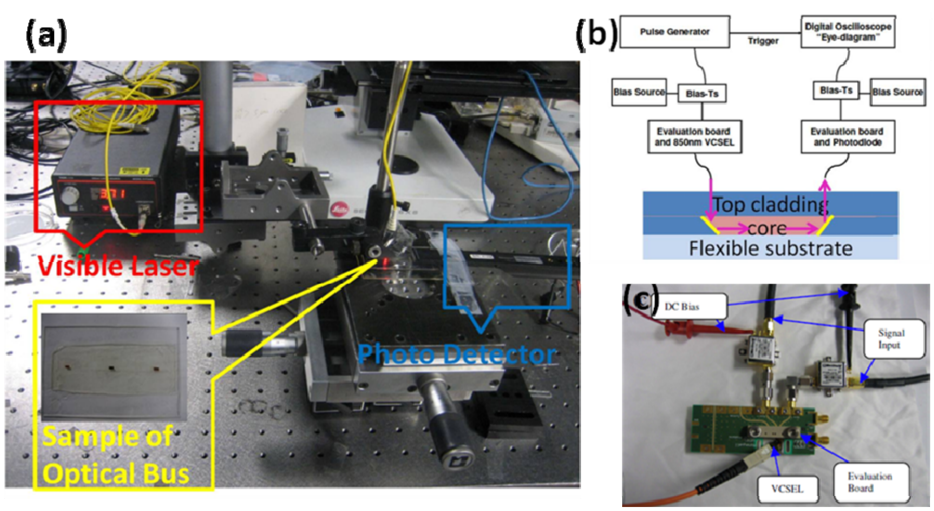


Figure 10 (a) using visible laser to make sure the optical bus works.
(b) connections in high speed data transmission test. (c) connections in the VCSEL evaluation board.

For high speed test, Figure 10(b) shows the diagram of the testing structure. The equipment includes a signal generator, evaluation boards for VCSEL, photodiode connections (shown in Figure 10(c)), device stage, DC power supply and oscilloscope for eye-diagrams. A 50/125μm multi-mode fiber is used to couple the light from the VCSELs to the waveguide. In order to increase the coupling efficiency, a drop of water is used as an index-matching medium between the MMF and bus waveguide nodes. High speed testing at 1Gbps and 10Gbps are carried out at 850nm. The testing operation details are described in Wang's paper[9]. The eye diagrams are successfully obtained for the optical bus waveguide from 1Gbps to 10Gbps, shown in Figure 11. The Q-factors of the eye-diagrams are measured with values from 6.23 to 4.67, respectively. The corresponding Bit-Error-Rates(BER) are calculated to be 2.3×10^{-10} and 1.5×10^{-6} for 1Gbps and 10Gbps, respectively if assuming the Gaussian distributed noise[9]. Further research work is on-going to reduce the insertion loss and increase the Q-factors for the optical bus waveguide device.

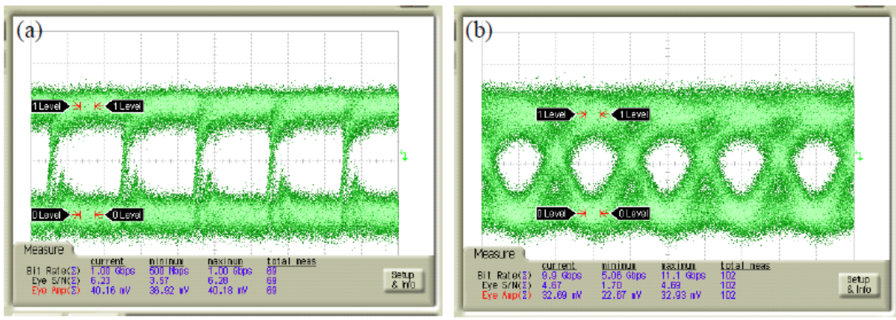


Figure 11 Eye diagram obtained showing the waveguide bus architecture is capable of transferring data signal of (a) 1Gbps and up to (b) 10Gbps

5. MOLDING NANO-SCALE FEATURES

The typical dimension for the bus architecture we discuss above is about 50μm. A similar process can be actually also used in structures with much smaller dimensions, for example waveguides of just a few microns and photonic crystal structure. Figure 12(a) and (b) shows the mold and imprinted result of a directional coupler structure with two 5μm width waveguides. The smooth surface can be observed using this method. Figure 12(c) and (d) show the photonic crystal waveguide structure with hole size of 243nm in diameter can be successfully replicated using nickel mold. When dealing with smaller dimensions, there are some extra concerns, for example, the choice of photo resist with proper thickness, the compatibility with the electroplating solution and the release agent for anti-stick purpose, etc. Typically, the mold should be rendered hydrophobic before it can be used to mold the polymer/resist. This molding method can greatly reduce the fabrication cost especially for those fine structures that can only be achieved by e-beam lithography.

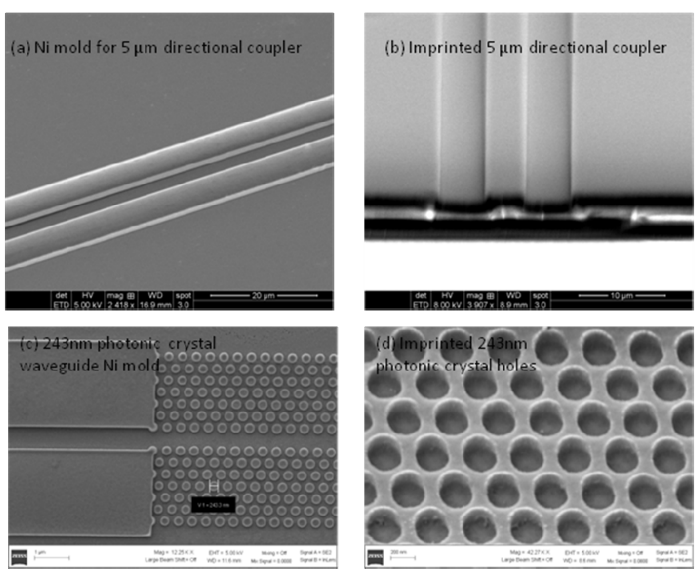


Figure 12 Electroplating nickel mold is used to print structures with dimension of 5μm and 250nm

6. CONCLUSION

We demonstrate a novel optical waveguide bus architecture which is capable of integrating as a backplane into the copper interconnects devices. Each node in the bus is able to send and receive optical signals from all the other nodes thus maximize the efficiency of data transmission. 45^{o} embedded mirrors are integrated to enables the vertical coupling from VCSELs. The fabrication process is introduced in detail from SU-8 pre-mold, nickel metal mold, molding to final device fabrication. Optical test shows the achieved waveguide bus can effectively transfer optical signals at 10Gbps speed. By applying mold method for such fabrication can greatly reduce the fabrication cost. Such fabrication method can also be applied to other optical components with smaller dimension, for example, directional coupler and photonic crystal waveguides in nano-scale.

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