Fully Embedded Board Level Optical Interconnects—From Point-to-Point Interconnection to Optical Bus Architecture

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Abstract: This paper presents the latest progress toward fully embedded board level optical interconnects in the aspect of optical bus architecture design, waveguide fabrication and device integration. A bidirectional optical bus architecture is designed and can be fabricated by a one-step pattern transfer method, which can form a large cross section multimode waveguide array with 45º micro-mirrors by silicon hard molding method. The waveguide propagation loss is reduced to 0.09dB/cm and the coupling efficiency of the metal-coated reflecting mirror is experimentally measured to be 85%. The active optoelectronic devices, vertical surface emitter lasers and p-i-n photodiodes, are integrated with the mirror-ended waveguide array, and successfully demonstrate a 10 Gbps signal transmission over the embeddable optical layer.

Key words: optical interconnects; optical bus; 45º micro-mirrors; hard molding; polymer waveguide; optical printed circuit board

I. Introduction

The speed and complexity of integrated circuits are increasing rapidly as integrated circuit technology advances from very-large-scale integrated (VLSI) circuits to ultra-large-scale integrated (ULSI) circuits. The number of devices per chip, the number of chips per board, the modulation speed, and the degree of integration continue to increase. The International Technology Roadmap for Semiconductors (ITRS) expects that on-chip local clock speed will constantly increase to 10 GHz by the year 2011[1]. The backplane frequency will boost proportionally to meet the interconnection requirement. The third-generation I/O protocol called peripheral component interconnect (PCI) Express, developed by the Signal Interest Group (SIG) consortium, is becoming an industry standard [2]. PCI Express is expected to increase transfer rates up to 10GHz in the next 7-10 years. Beyond 10GHz, copper interconnects on PCB made of FR4 material, become bandwidth limited due to losses such as the skin effect in the conductors and the dielectric loss from the substrate material. It has been reported that replacing the flame resistant 4 (FR4) material with newer laminates such as Rogers 4000 can extend the bandwidth of electrical interconnects to 7.7GHz, but increase the cost by five times [3]. Besides the cost issue, several much worse situations for electrical interconnects are introduced by the unsolvable frequency dependent loss, reflection and cross talk.

Optical solutions, which are widely agreed as a better alternative to upgrade the system performance, have been proposed for the upcoming electrical interconnect bottleneck for over 20 years [4]. Optical interconnects preponderate over the copper links in immunity to electromagnetic interference,

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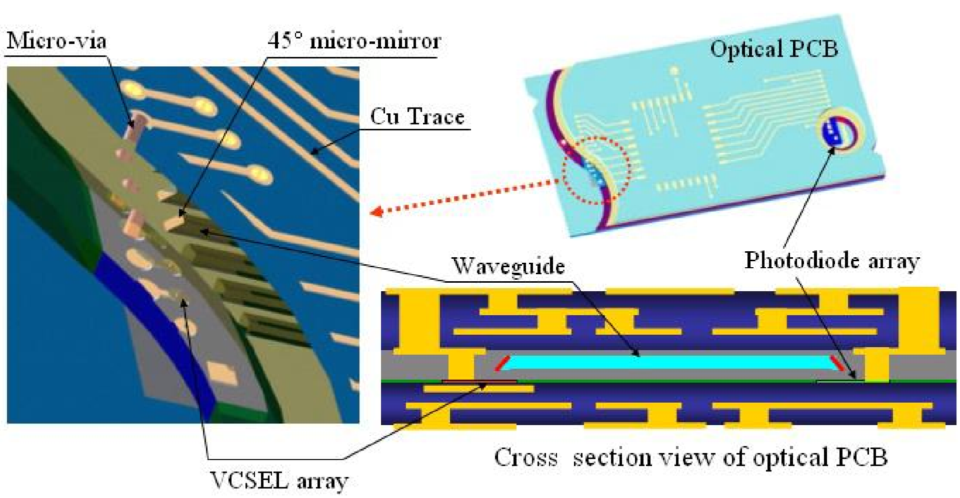
independency to impedance mismatch, less power consumption, and high speed operation. Many optical interconnects schemes have been proposed and investigated, including free space [5], embedded fiber connection [6] and optical slots [7]. However, most of them can only provide a unidirectional point-to-point interconnection. Additionally, these optical interconnects implementations lack a seamless interface with electrical components from the system packaging point of view. For example, the board level optical interconnections reported in [5] piled up lasers, detectors and micro-lens on the surface of a printed circuit board (PCB). The difficulties regarding packaging, multilayer technology, and reliability still remain to be solved.

We previously introduced a fully embedded board-level optical interconnects to relieve the packaging difficulty [8]. And later on, another paper was published to describe the fabrication of flexible optical waveguides, thermal management of embedded thin-film vertical surface emitter lasers (VCSELs), and optical layer integration with VCSELs and photodiode arrays [9]. In this paper, the latest progress to fulfill the fully embedded optical interconnects with optical bus architecture is presented. An improved fabrication procedure of a large cross section multimode waveguide array with 45º micro-mirrors by one-step pattern transfer method is presented. Low propagation loss waveguides as well as high coupling efficiency micro-mirrors are experimentally obtained and measured, using a new fabrication process in contrast to Ref. 9. The active optoelectronic devices, VCSELs and p-i-n photodiodes, are integrated with the mirror-ended waveguide array, and successfully demonstrate a 10Gbps signal transmission over the embeddable optical layer for the first time.

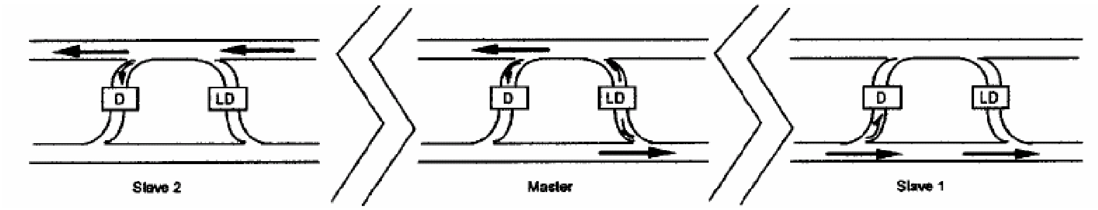
II. Fully Embedded Board Level Optical Interconnects based on Optical Bus Architecture

For electrical interconnects, the point-to-point topology has replaced the shared-bus topology because of its bandwidth. However, wiring congestion is the adverse consequence of this transition, because in order to route all memory modules to the central switch, the boards in a high performance computing system currently tend to use more than 50 wiring layers, and more than 700 signal pins are required for one board edge connector, which needs as large as 100 pounds insertion force to seat [10]. Optical bus architecture [11-12] greatly mitigates the wiring congestions, while still allows multiple daughter boards to share a common data channel to transfer information at a high speed simultaneously. There is no loading effect of optics analog to driving capacitance in electronic circuit, which means the signal propagation speed is a constant value of 0.6c of polymer waveguide regardless of the presence of the receiver boards. While for electrical bus, an unloaded PC board trace has a typical signal propagation speed of 0.6c to a fully loaded bus line of 0.2c. Higher speed as well as a much more stable signal round-trip time can be obtained by replacing the electrical bus with the proposed optical bus. Comparing with point to point interconnect, bus based interconnects represent the most complicated interconnect structure with full interconnectivity and broadcasting nature. Fiber based optical interconnects, which is intrinsically for point-to-point interconnection, fails to provide the desired optical bus architecture. As a comparison, polymer waveguides can be easily manipulated to form a complicate interconnection structure that is indispensable for a bi-directional optical bus [8,13].

The architecture of the fully embedded optical layer includes a VCSEL array, a p-i-n photodiode array, surface-normal micro-mirrors, and a polymeric channel waveguide array with 45° micro-mirrors functioning as a physical layer of optical interconnection. The driving electrical signals to modulate the VCSELs and the demodulated signals received at the photodiode flow through electrical vias connecting to the surface of the PC board, as seen in Fig.1 (a). Within the optical interconnect layer, the light from the VCSELs is coupled into/out of the waveguide through 45° micro-mirror couplers and propagates in the polymer waveguide. The fully embedded structure 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 high-performance microelectronics is the packaging incompatibility. Fig.1 (b) shows the in plan view of the optical equivalent of a single bidirectional electronic bus line. The optical waveguide plane consists of two parallel optical buses, which can transmit optical signals toward two opposite directions. Optical signals, either from laser diodes (LD) of the master unit or the slave units, will be transmitted bidiretionally through two connected unidirectional couplers. The detectors (D) of either the master unit or the slave units are capable of receiving optical signals from both directions also, benefited from the two unidirectional couplers connected to them. The two parallel optical buses in conjunction with unidirectional couplers ensure the completely non-blocking interconnection among any existing units, without any wiring congestions. The laser diodes and photodectors belong to another plane. The drive current provided by each electronic transceiver powers the corresponding laser diode, whose output is split and injected into both unidirectional couplers. Each photodiode detects light from either unidirectional coupler, whose current powers the corresponding electronic receiver. The laser diodes and the photodetectors are located either on the associated cardboards or the backplane itself. The intra-plane interconnection, i.e., from the laser diodes and photodectors to the waveguides, are established through surface normal micro-mirrors.



(a)

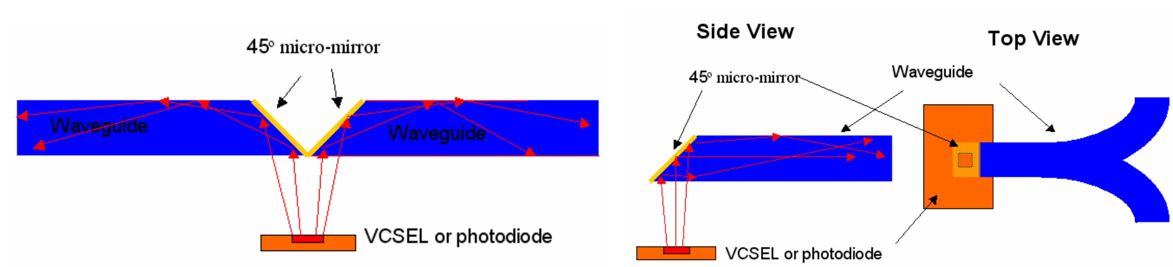


(b)

Fig 1 (a) Fully embedded board level optical interconnects architecture (b) In plane view of the optical equivalent of a bidirectional electronic bus line driven by open-collector drivers (D: detector, LD: laser diode, coupling to the in plane waveguide through 45° mirror)

The optical waves can be either coupled into and out of the optical bus by two opposite-placed 45º micro-mirrors, as Fig. 2 (a) shows, or by one micro-mirror and equally split by a Y-branch coupler, as Fig 2 (b) shows. The fabrication process for the bidirectional bus structure is completely compatible with that for the parallel point-to-point optical interconnects.

To fulfill the embedded structure, two major stumbling blocks need to be solved. A low cost, high performance optical layer on a polymer thin film represents the first. Packaging the optical layer through via holes and laminating it inside PCB layers stands for the second. The research work presented herein will relieve the concerns for the first major block, and is believed to be able to accelerate the deployment of the fully embedded optical interconnect architecture.



(a) (b)

Fig 2 3D bidirectional intra-plane couplings through (a) two opposite placed 45º micro-mirrors and (b)one 45º micro-mirror and one Y-branch coupler

III. Fabrication of Waveguide Array with Micro-Mirrors

We previously demonstrated a soft-molded waveguide layer with 45º coupling mirrors that is suitable for the embedded structure [14]. Soft molding method utilizes properly shaped flexible molds—often made of elastomeric polydimethylsiloxane (PDMS) for pattern transfer. Although cheap and easy for fabrication, soft molding method still faces serious problems such as durability and size precision. Due to its low Young's module, the soft mold will deform even under a small pressure, resulting in a reduced channel depth and enlarged pitch distance. This expanded pitch will cause the waveguide alignment difficulty with the VCSELs and photodiode array resulting in increased coupling loss. These shortages can be overcome by replacing the soft mold material with silicon based hard mold.

Although the silicon master mold, fabricated by photolithography and deep reactive ion etching (DRIE) method, is more expensive than the PDMS soft mold, the production cost per waveguide array is still cheaper than soft-molding method when considering its long durability.

A hard molding fabrication process using UV embossing method is conducted on a 100µm thick topas film. The topas film is chosen because of its transparency and high glass transition temperature (Tg>160ºC) [9]. The main procedure is divided as the following steps shown in Fig.3:

(a) First, a layer of UV curable bottom cladding material, WIR30-450 (from ChemOptics, with a refractive index of 1.45 at 850nm wavelength) is spin coated on the topas film substrate.

(b) In the second step, the master mold is brought in contact with the spin-coated substrate, and the molded WIR30-450 layer is UV cured for 8 minutes inside a nitrogen atmosphere.

(c) To separate the polymer substrate with the silicon master mold, the sample is immersed in acetone to quickly dissolve the photoresist layer on top of the silicon pattern. The intact polymer substrate will detach the master mold within 1 minute. After forming the desired trenches, a core material WIR30-470 with a higher refractive index (1.47 at 850nm) is used to fill them up. The excess polymer is scraped off, and the same amount of UV dose is applied to cure the core layer.

(d) In the last step, the sample is spin coated with another layer of WIR30-450, which functions as the top cladding, and followed by a UV curing process.

Unlike hot embossing [15] or PDMS soft-molding [9] methods, there are no fabrication steps associated with high pressure or heating. This ensures the replicated waveguide array to have an exact size as the original silicon master mold, and thereby reduces the fabrication cost and energy consumption. The propagation loss of the waveguide is measured by the cutback method. An 850 nm VCSEL light is coupled into the waveguide by a 50/125µm graded index multimode fiber and the output beam is then coupled into a photodetector by a 62.5/125µm graded index multimode fiber. The measured propagation loss is 0.09dB/cm at 850 nm. This data is close to the planar waveguide loss of 0.05dB/cm provided by the material vendor.

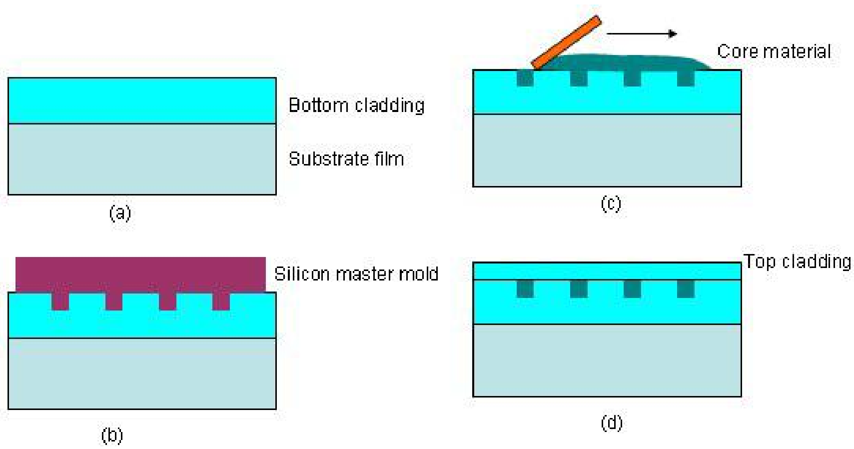
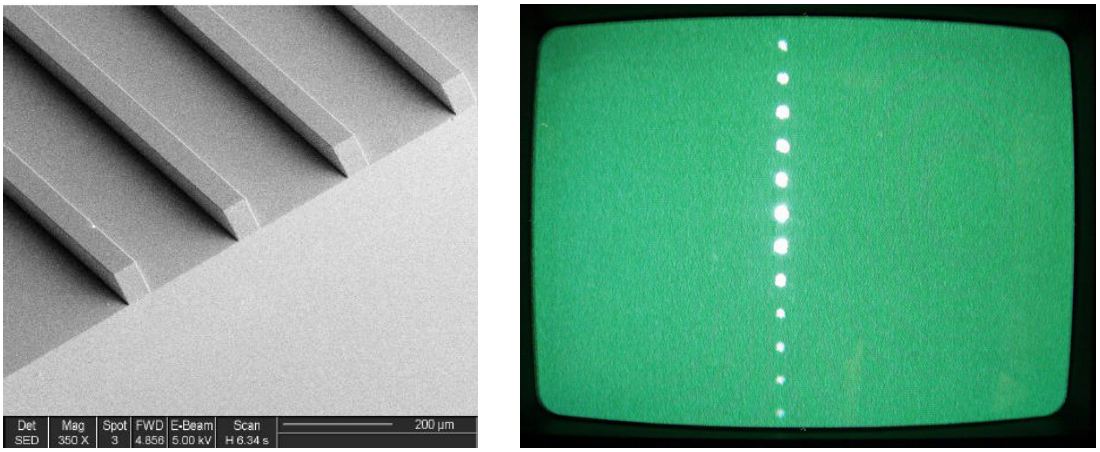


Fig.3 UV embossed molding process of the polymer waveguide array

Waveguide couplers play a key role for the realization of three-dimensional fully embedded board-level optical interconnection owing to their surface-normal coupling of optical signals into and out of in-plane waveguides. A waveguide grating [8] as well as a 45º waveguide mirror based coupler [14] can serve as a surface normal coupler. However, the grating based approach requires precise control of grating parameters for efficient coupling and usually has a low tolerance to wavelength variations. Therefore, we employ 45° total internal reflection (TIR) coupling mirrors at both ends of waveguides because they are easy to fabricate, reproducible, and relatively insensitive to wavelength variations, and can provide a high coupling efficiency.

The waveguide micro-mirror can be fabricated by a one-step pattern transfer method described in [14]. After the DRIE process, the silicon master mold is mechanically polished on both ends using a specially designed 45º stage. The polishing process starts from a 30μm grits lapping pad to 1μm grits. Finer polishing is unnecessary since the following spin-coated surface treating process will smear the remained roughness. The 45º tilted end surfaces will be transferred to the UV cross linked polymer substrate that is in direct contact with the master mold. The waveguide array pattern, together with the desired micro-mirror coupler, is replicated in a negative shape from the master structure simultaneously. To further reduce the fabrication effort described in [14] using standard photolithography and followed by lift-off process, the sample is covered by a polymer thin-film mask with opened mirror windows. This reusable thin film mask will shield the deposition of metal layer on the polymer substrate except in the open windows. An electron beam evaporated 200nm thick gold layer is deposited to form the high reflectivity mirrors. After removing the thin film mask, the UV embossed trenches with metal mirrors on both ends, can be filled with the core material.

The SEM image of the polished surface on the silicon master mold is shown in Fig.4 (a). To observe the light transmission over the UV embossed waveguide array with the embedded 45º micro-mirrors, a 9μm core diameter fiber coupled with a 633nm He-Ne laser vertically launch the input light into the waveguide mirrors. The input fiber is purposely pulled 5mm above the mirror surface to co-illuminate the 1X12 mirror array. At the back end, the output field patterns are projected onto an image scope, which can be viewed through a monitoring screen. The output pattern of the twelve reflecting mirrors is shown in Fig.4 (b). We measured the total insertion loss of the twelve channels at 850nm wavelength. By comparing the results with the values for straight waveguides of the same length and dimension, we extracted the total coupling loss of the front and back mirrors. Assuming the two mirrors have the same coupling efficiency, which is approximately correct, the obtained coupling loss is 0.7~1.5dB for each mirror. In another word, the highest coupling efficiency is 85%.



(a) (b)

Fig.4. Experimental results of the micro-mirror array (a) SEM image of the silicon master mold with polished surface (b) output pattern from the image screen

IV. Prototype system demonstration

Figure.5 shows the testing setup for the prototype optical layer, which is embeddable to the PC boards, with an enlarged view of the microwave probes approached to the integrated photodiode array.

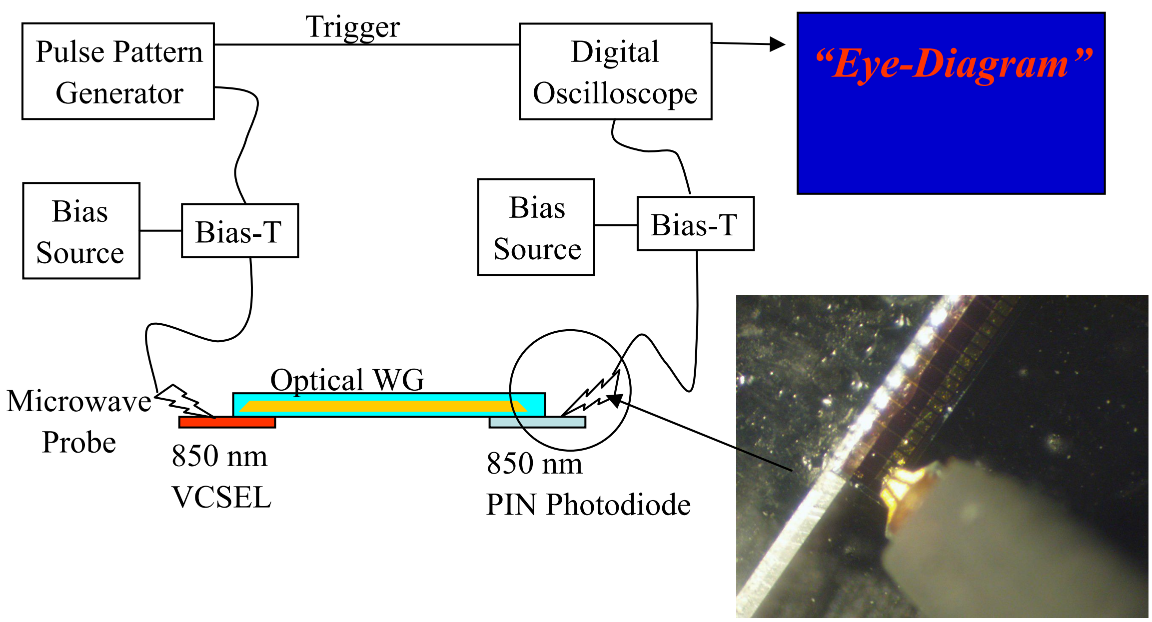


Fig.5 Schematic diagram of the measurement setup for the assembled optical system

The VCSEL is biased with a lasing current, and the photo current from the p-i-n diode is measured as well. The maximum response from the photodiode is 300μA.The VCSEL is then biased at 5mA and modulated by a ±0.3V 10 Gbps pseudo random signal. The response from the photodiode is directly connected to a digital oscilloscope without any pre-amplification. The measured eyediagram is shown in Fig.6, with a Q-factor of 7.24, corresponding to a bit error rate (BER) below 10^{-12}.

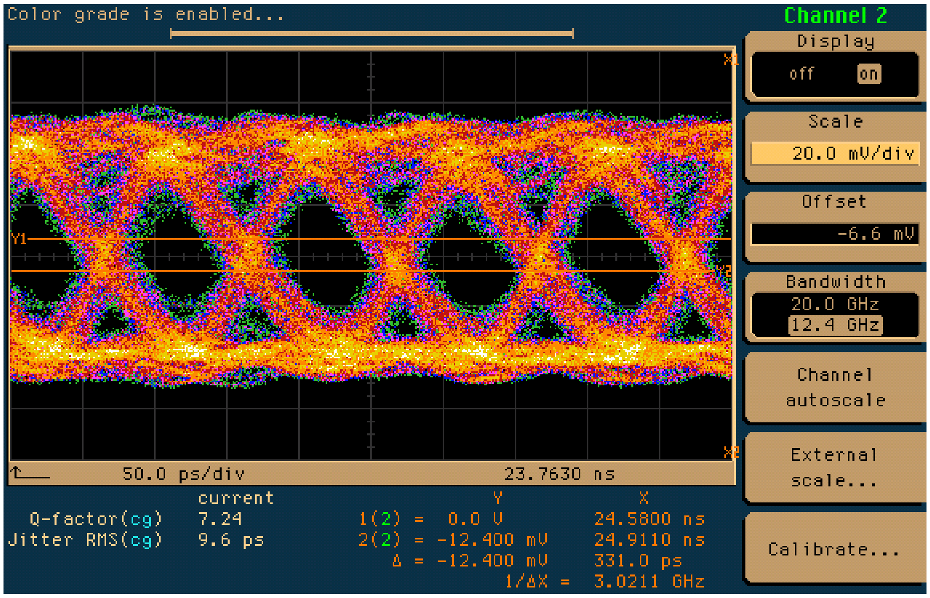


Fig.6 Measured 10Gbps eyediagram with a Q-factor of 7.24

V. Conclusion

This paper presented the latest progress of device fabrication and system integration for fully embedded board level optical interconnects based on optical bus architecture. Further investigation including metal plate molding process, bi-directional bus structure, and integration with printed circuit boards will be conducted.

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