Integrated Micro-Cylindrical Lens with Laser Diode for Single-Mode Fiber Coupling

Yongqi Fu, Ngoi Kok Ann Bryan, Ong Nan Shing

***Abstract*—The integration of laser diode with microlens on its emitting surface is introduced in detail in this paper. Calculated results are based on integration of micro-cylindrical lens to laser diode. The lens is directly microfabricated on the emitting surface of the laser diode with operating wavelength 635nm by focused ion beam (FIB) SiO_2 deposition function. The controlled SiO_2 deposition process is realized by programming of our FIB machine. Using single-mode fiber with core diameter of 10 μm as testing prototype, coupling efficiency of the compact and miniaturized system reaches as high as 80.1 %. Measured far field angle (full angle) is 2.1° and 31° with and without the lens respectively.**

Index Terms—Edge-emitting laser diode, micro-cylindrical lens, FIB, deposition, fiber coupling

I. INTRODUCTION

IT IS well known that laser diode is very popular in fiber communication. Many methods for solving the key problem of fiber coupling have been introduced in the past [1]~[6]. In this paper, a new coupling method has been introduced, integrating of laser diode with microlens that deposited directly onto laser diode using focused ion beam direct deposition technology. By depositing SiO_2 on the emitting surface of laser diode, microlens with spherical or aspherical shape can be formed to realize collimating or focusing of the laser beam directly from the emitting surface. Miniature and compact structure of the optical system can be realized through this way, which eliminate the conventional separation optical structure, above all, the coupling efficiency is improved.

II. DESIGN

The laser beam is divergence in both parallel and transverse directions, as shown in Fig.1. It is necessary to collimate the beam from the two direction. Refractive power of the microlens in both *xoz* plane and *xoy* plane are needed from the theoretical point of view. Normally, the divergence angle in the direction of parallel $\theta_\perp$ is much larger than the transvers $\theta_{||}$.

For the purpose of fiber coupling, the micro-cylindrical lens is used based on the following consideration:

in case (a) (shown in Fig.2 in *xoz* plane)

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \qquad (1)$$

in case (b)

$$n_1 \sin \theta_1 = n_3 \sin \theta_3 \qquad (2)$$

where

- n_1 refractive index of laser diode medium;
- n_2 refractive index of air;
- n_3 refractive index of cylindrical lens, here is n_{SiO2};
- θ_1 transmission angle in laser diode medium;
- θ_2 emitting angle of laser diode;
- θ_3 transmission angle through micro-cylindrical lens along transverse direction.

Known parameters are n_2=1, n_3=1.46, θ_2=7° (provided by supplier of AlGaInP Index Guided MQW laser diode with power of 5 mW), and θ_3 can be calculated by formula (1) and (2), that is θ_3= 4.79°.

In order to achieve optimum coupling, θ_3 should satisfy the conditions: $\theta_3 \le \theta_4/2$, where θ_4 is full reflection angle of single-mode fiber core.

For the fiber under test, the full reflection angle is 12°, thus $\theta_4/2$ is larger than calculated θ_3. Therefore, the laser mode in the *xoy* plane is matched to the fiber mode and does not require refractive power from the lens in this dimension. Thus, the refractive power of the lens in the *xoz* plane is needed to match *x* component of the laser beam (which is rapidly expanding) to the fiber mode.

In the parallel direction, from the theoretical point of view, it is better to design aspherical form as compared to spherical form due to its small spherical aberration. However, considering the fabrication constrains, spherical form was selected because the form accuracy is easier to be archived by the direct FIB SiO_2 deposition process. The lens can be regarded as plano-convex micro-cylindrical lens with spherical form in the *xoz* plane, and its focus length *f* can be obtained according to the plano-convex lens with focus length formula ($f = R/(1-n_{SiO2})$) (*R* is radius of spherical lens, and can be calculated in terms of the required *f*). Considering the strip width of the laser ω=45μm, we set the lens dimension of 50 μm in length, and 5μm in width so that the strip can be fully covered by the lens. For a designed wavelength (*f*) of 32μm, the calculated radius of the spherical is 15μm, and f-number and NA value is 6.5, and 0.08 respectively, The micro-cylindrical lens sizes are determined in terms of the strip width as 50μm×5μm×0.85μm in length, width and height respectively (here, the height of 0.85 μm is calculated by the width of 5 μm).

III. MICROFABRICATION

Focused ion beam technology is used for the fabrication of the lens. Ga^+ ions are focused to spot size of several nanomaters on the sample surface. Material of the surface is removed by process of collision between the ions and the sample molecules. SiO_2 deposition can be realized by adding source gas (Silicon and Oxygen) into the process. Detailed information about FIB working principle can be found in Ref.[7].

SiO_2 can be deposited directly to form a required pattern using FIB deposition function. The source gas is decomposed by ion beam and adsorbed by substrate surface. The entire process is

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Publisher Item Identifier S 1041-1135(00)07876-9

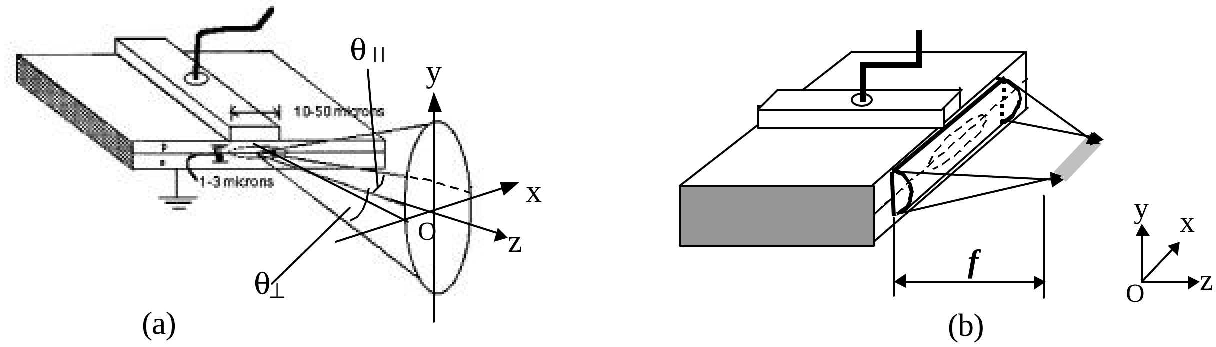

Fig.1 Schematic of laser diode structure. (a) diagram of original laser diode; (b) integrated micro-cylindrical lens with the laser diode. The microlens with size 50×5×0.85 μm covered on the emitting facet.

controlled by computer program in terms of relationship between ion beam energy and deposited thickness.

Experiments are carried out on our FIB machine Micrion 9500EX with ion source of liquid gallium integrated with scanning electron microscope (SEM), energy dispersion X-ray spectrometer (EDX) facilities and gas assistant etching (GAE) functions. This machine uses a focused Ga^+ ion beam with energy between 5~50KeV, a probe current between 4pA~19.7nA and beam limiting aperture size between 25μm~350μm. For the smallest beam currents, the beam can be focused down to 7nm in diameter at full width and half magnitude (FWHM). For the deposition of SiO_2, the source gas is 1,3,5,7 tetramethylcyclotetrasiloxane (TMCTS), with the ion energy set at 50keV, and chamber vacuum maintained at 1.23×10^{-6} Torr throughout the entire process. Because the entire process is carried out under room temperature, damage to the emitting facet of the laser is minimized. Furthermore, the source gas is harmless to the emitting facet.

Pressures of O_2 and Siloxane are key factors controlling the composition of Oxygen and Silicon of the deposited SiO_2 which determine transmission properties of the SiO_2. The transmission properties are best at the standard compound percentage of SiO_2 (Si: 46.74%, O: 53.26%, calculated by atomic weight) which can be obtained by adjusting the pressure of O_2 and Siloxane. Through deposition experiments and EDX analysis, the ideal pressure is 0.852 Torr and 0.206 Torr for Oxygen and Siloxane respectively, and corresponding compound of Silicon and Oxygen is 45.91 % and 53.79% respectively (Ga: 0.3%). In addition, a little Ga^+ element mixed in the SiO_2 has been observed which is due to unavoidable ion implantation during the process which affects transmission of the lens to a certain extent.

The continuous relief curve is converted to discrete point data used for motion control according to machine's scanning step initially, and for each discrete height, the required ion dose is calculated according to the calibrated relationship between deposited height and ion dose, as shown in Fig.3. The deposition process is carried out automatically by our machine's programming function in terms of the calculated ion dose. The fabrication process of the lens can be seen in Ref.[8] in which it was introduced and analyzed in detail.

IV. EXPERIMENTAL RESULTS

The coupling efficiency measurements were obtained by first measuring the total output power of the laser diode with operating wavelength of 635 nm using an integrating sphere. The laser diode on chip is used for the sequential measurement so that the detector could approach the emitting surface as near

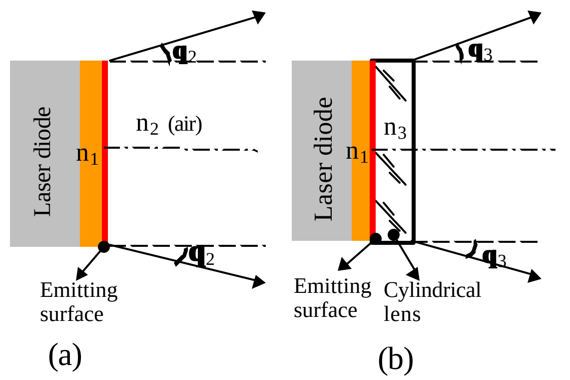

Fig.2 Schematic of laser diode beam transmission along xoz (transverse) plane. (a) propagation in air, (b) propagation through microlens along *xoz* plane

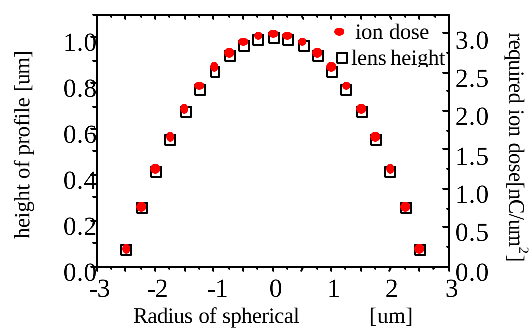

Fig.3 discrete relief curve and vs calibrated ion dose

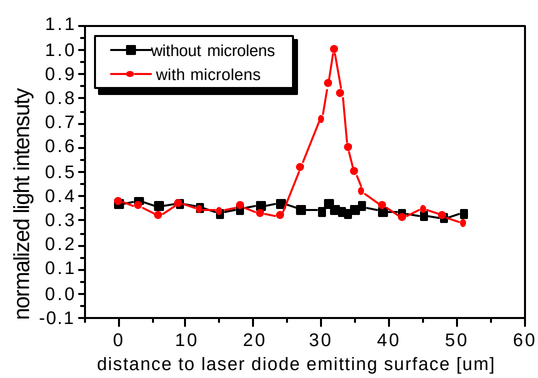

Fig.4 light intensity of the laser diode with and without the microlens measured by BeamScope-5P™ beam scanner as possible. The power coupled to the fiber was determined by measuring the power at the output of the fiber using the same integrating sphere. The integrated laser diode was positioned using a three axis piezoelectric micromanipulator. The coupling efficiency was measured by single-mode fiber with core diameter of 10µm, full reflection angle 12°, and cleaved angle of 60° at the end of the facet. It was shown by experiment that displacement perpendicular to the junction is considerably more sensitive to coupling than they are in the orthogonal direction.

In order to evaluate the effect of fabrication process to the laser diode performance, normalized light intensity curve is derived at focal plane before and after the application of the micro-cylindrical lens without a fiber into the integrating sphere, which is measured by BeamScope-5P™ beam scanner, as shown in Fig.4. It can be seen that there is only a little influence on the output intensity of the laser diode in the process of FIB deposition, which is acceptable for the application of the fiber coupling. Figure 5 presents far field angles (full divergence angle) of the laser diode with and without the lens in the parallel direction. It shows that the measured far field angle is 2.1° and 31° with and without the lens respectively. It shows that the transverse far field angle is reduced greatly to a certain extent.

The measured coupling efficiency has improved greatly to 80.1% compared to the efficiency of 42% without the lens. The coupling efficiency measured here could be enhanced by the use of a suitable antireflection coating at the head of the fiber facet [6] and reducing microfabrication error and measurement misalignment error.

V. CONCLUSIONS

On the basis of above experimental results, the following conclusions can be drawn

- The method of directly depositing SiO_2 on the emitting surface of laser diode by FIB technology is practical and available.
- Miniature and more compact structure can be realized by this way. The patterning deposition of SiO_2 makes it possible to find applications in the post-processing of surface-relief microstructures to add specific micro-optical elements accurately on the micro-devices, such as micro-opto-eletric-mechanical system (MOEMS).
- This method is also available for other microlens deposition such as elliptical, and spherical/aspherical refractive/diffractive microlens.
- The coupling efficiency of the integrated system has exceeded the normal fiber communication requirement.

In addition, focusing characteristics can be improved further by degrading curvature of the spherical form so that the form accuracy can be controlled more accurately during the fabrication process.

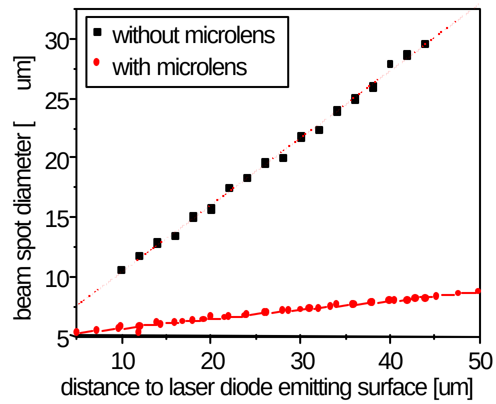

Fig.5 far field angles (full divergence) measured by BeamScope-5PTM beam scanner, the angle is 2.1° and 31° with and without the fabricated micro-cylindrical lens respectively.

ACKNOWLEDGMENT

This work was supported in part by the funding for Strategic Research Program on Ultra-precision Engineering from the NSTB (National Science & Technology Board, Singapore) and Research Funding (ARC 9/96) from Nanyang Technological University. The Authors would like to thank Dr. Zhou Xiaoqun and Mr. Shen Zhongwei for their helpful discussion, Mr. Chin Chee Sing for his enthusiastic checking of the paper, and Lim Boon Hong for assistance in the experiments.

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