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Design and fabrication of a biconvex aspherical microlens for maximizing fiber coupling efficiency with an ultraviolet laser diode

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A B S T R A C T

This paper introduces a biconvex microlens to maximize the light coupling between an edge emitting laser diode (LD) and an optical fiber. Both convex surfaces have different profiles along their x- and y-axis so that the elliptical light beam from an LD can be fed into the core of a fiber. The optimized lens profiles are first simulated by the ray-tracing software Zemax and then fabricated by an excimer laser micromachining system. Focal spot size around 10 μm is achieved experimentally. Light coupling efficiency using this single biconvex microlens is 31.8% and 47.6% for single-mode and multi-mode fiber, respectively.

1. Introduction

Laser diodes (LDs) are one of the most important light sources widely used in our daily lives and with great potentials for a wide range of engineering applications. Important advantages of LDs are compact size, high efficiency, good reliability, broad wavelength range, small emissive area compatible with fiber core dimensions, and possibility of direct modulation at relatively high frequencies. In many applications, light emitted from a LD needs to be coupled into an optical fiber and the coupling efficiency becomes an important issue. Challenges of light coupling stem from the fact that LD light sources can be quite complicated. Taking an edge-emitting LD as example, the output laser beam has an elliptical intensity profile associated with certain degree of astigmatism. Another difficulty of light coupling between LDs and optical fibers is that in some cases the fiber core dimension can be very small. One example which is particularly important in this work is a single-mode fiber (SMF) working at ultraviolet (UV) wavelength. The core diameter of this SMF is only 3 ∼ 4 μm and therefore effectively coupling to a LD becomes challenging.

An idea of aspherical microlens for fiber coupler of edge emitting LD has been proposed [1,2]. These Micro-cylindrical lenses and micro-elliptical lenses directly fabricated by focus ion beam (FIB) on silicon dioxide (SiO2) layers deposited on a LD surface can significantly increase the coupling efficiency. Plano-convex microlens and ball lenses have been introduced to enhance the coupling efficiency of a high power LD to a single mode fiber [3–6]. Wedge-shaped, anamorphic shaped, hemispherical shaped microlenses and asymmetric ellipticcone-shaped microlenses fabricated at fibers' end-surfaces were proposed to gives higher coupling efficiency [7–10]. The proposed methods combine grinding and polishing techniques to make the fiber end surface tilted with an angle and hence obtaining higher coupling efficiency. Diffractive optical elements (DOEs) had been directly fabricated on top of a cleaved SMF [11]. It demonstrated higher coupling efficiency between a SMF and a waveguide using a micro-lens technique. Micro-optical device with two aligned DOEs was designed and fabricated by direct laser beam writing, and lithography technique in photoresist to achieve high multi-mode fiber (MMF) coupling efficiency [12]. Inorganic-organic hybrid sol-gel material was used to fabricate microlens array by direct laser writing and conventional reflow technique hence coupling efficiency was greatly improved [13,14]. The semi-ellipsoid microlens was designed and fabricate on optical fiber faces by photolithography to obtain low coupling loss [15–17]. Negative-tone photoresists were used to form a cone-shaped microlens at fiber's end surfaces and enhanced MMF coupling efficiency was demonstrated [18]. Achromatic doublet microlens was also used to improve the coupling efficiency of single-mode fiber [19].

The majority of LD-fiber coupling methods discussed above are for optical communication at wavelength around 980 nm to 1550 nm. Very limited attention has been given to UV LDs which work at a relatively shorter wavelength. Recently, UV LDs have been considered as the light source for photolithography [20–23].

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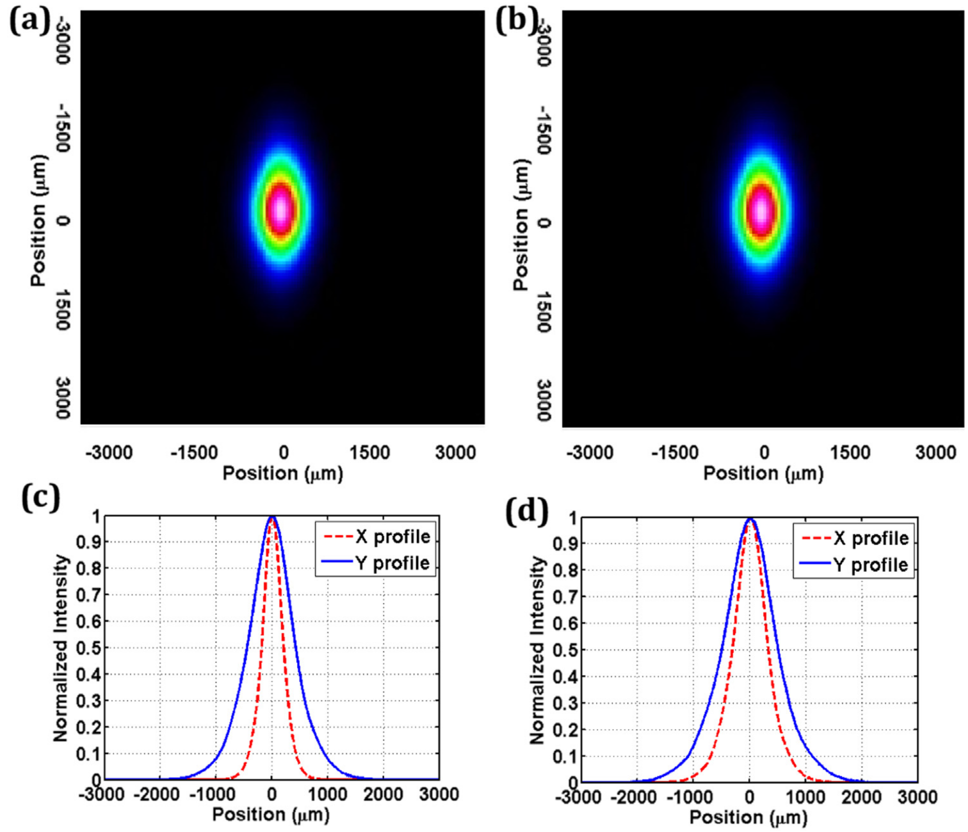

Fig. 1. Normalized light intensity profiles of the UV-LD measured at (a) $z = 2.1$ mm and (b) $z = 3.1$ mm, (c) and (d) are the cross-sectional intensity profiles along x/y-axis in (a) and (b), respectively.

In these applications, UV light from a LD with wavelength around 365–430 nm needs to be coupled into an optical fiber. A single-mode optical fiber is preferable because the UV light coming out from the other end of the fiber can be viewed as a point light source with well-defined mode shape, and hence has many advantages for subsequent optical processing and handling. A fabrication method using contour mask scanning method of excimer laser also has been proposed by the authors [23–25].

In this paper, a single biconvex microlens fabricated by excimer laser micromachining method is proposed to maximize the coupling efficiency between a UV-LD and a single-mode fiber. The key issue in this approach is to precisely control both surface profiles of the biconvex microlens so that the elliptical and astigmatic laser beam can be focused into a small circular spot with a dimension close to the core diameter of the fiber. Experimentally, a commercial edge-emitting UV laser diode (DL5146-101S, Sanyo Electric Co., Tokyo, Japan) is used and it has a wavelength of 405 nm and a maximum power of 40 mW under a current of 70 mA. This LD is going to be coupled with a SMF (S405-XP, Thorlab. Inc.) which has a numerical aperture (NA) value of 0.12, an acceptance angle of 13.6°, this angle is full angle so that NA = sin(13.6°/2) ≈ 0.12 and a fiber core diameter of 3.3 μm.

2. Design and optimization of aspherical biconvex microlens

For simulating and optimizing the biconvex microlens, it is very important to know the light source characteristics. Laser beams from edge-emitting LDs are known to have two different divergence angles along its fast (or x-) axis and slow (or y-) axis and hence has an elliptical beam profile. To experimentally characterize its optical characteristics, the LD laser beam used in this work is first measured by a scanning slit beam profile meter (BP209, Thorlab. Inc.) at two different locations of its optical axis, or the z-axis, which is originated from the LD's output glass window. Fig. 1(a) and (b) show the normalized intensity profile measured at z equal to 2.1 mm and 3.1 mm, respectively. Fig. 1(c) and (d) show the cross-sectional profiles along x/y-axis in Fig. 1(a) and (b), respectively. Excellent Gaussian beam profiles are observed. Based on the measured profiles, the fast- and slow-axis divergence angles at 4-sigma

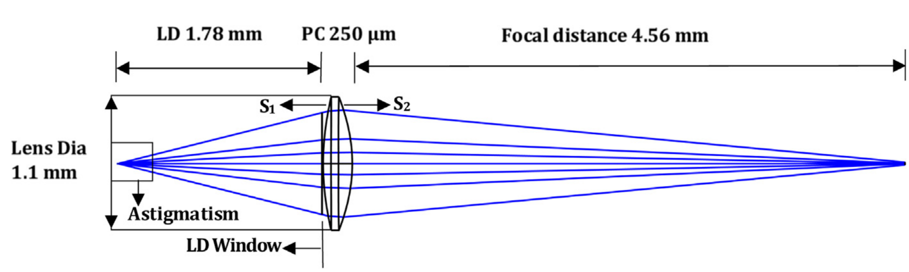

Fig. 2. Zemax simulation of light coupling between a UV-LD and a SMF using a single biconvex microlens.