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Study of beam divergence of a fiber-bundle prism-coupled waveguide using ray tracing

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ABSTRACT

Experimental and theoretical results of a two-stage beam shaping system based on a flexible plastic fiber-bundle and a prism duct are described in this study. An imaging technique is used to investigate the divergence effect on the output beam images and intensity profiles. Photograph pictures of the output beam at different axial distances are taken by a digital camera and the image data is converted into a response curve and presented in this study. According to the experimental results, the propagation in the free space transforms a square beam with a hat-top intensity distribution into a rectangular beam with a conical intensity distribution. For theoretical investigations, using VOB software a simulation is performed to analyze the reported beam shaping design. Ray tracing diagrams are presented to study the direct beam propagation, refracted rays and total reflection rays. The prism duct output beam dimension is determined as a function of distance from the prism exit face and the optimum condition for the maximum power transmission and best image quality is reported. The calculated output beam dimensions by VOB are compared with the experimental ones and there is a good agreement between the observed results.

1. Introduction

In recent years there are very large demands on using beam shaping methods in different areas including material treatment, data storage with laser beams and solid-state laser pumping etc. It is possible to modify beam geometrical cross section and improve beam amplitude and phase using such techniques. Both the geometrical and physical optics have been used to develop a variety of the beam shaping systems. Beam shaping; in general, can be based on principles such as diffractive and refractive optics by using different optical devices such as lenses, gratings and collimators. For instance, an elliptical lens for laser beam shaping is described in Ref. [1]. Also shaping the beam profile of an elliptical Gaussian beam by an elliptical phase aperture is reported [2]. An adaptive beam shaper based on a single liquid crystal cell is presented in a report [3]. In another study the required mirror profile for X- ray beam-shaping via deformable mirrors are analytically computed [4]. Generation and versatile transmission properties of ring-shaped beams based on thermal lens effect of magnetic fluids and ring-limited windows are described in literature [5]. A novel hybrid algorithm for the design of diffractive optical elements for beam shaping is studied in [6].

Micro lenses are other devices to modify the beam shape. High energy-efficient agricultural lighting by B + R LEDs with beam shaping using micro-lens diffuser is presented [7]. Design and fabrication of aspherical micro-lens used for beam shaping of vertical-cavity surface emitting lasers is also studied [8]. Grating can be another means for the beam shaping optics. Numerical analysis of spectral shaping based on superstructure fiber Bragg grating in high-power Nd:glass chirped pulse amplification system is presented [9]. Interferometry is another method for changing the beam shape and a common-path interferometer including integrated single-prism beam shaping is presented in [10]. Also in a report [11] nonlinear filtering and beam shaping with a nonlinear polarization interferometer is described. By using a high-efficiency and accuracy holographic tandem method an arbitrary beam shaping is accomplished [12].

There is a wide range of applications, which benefit from processing of redistributing the irradiance and phase of optical radiation beams. A paper by Ref. [13] describes adaptive beam shaping for improving the power coupling of a two-Cassegrain-telescope. In another report, a laser assisted direct write process with novel beam profiles is described [14]. It is also useful to check variation of the beam shape in different beam shaping media. For example,

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a report by Ref. [15] explains characterizing the divergence properties of the laser diode beams propagation through collimator and aperture optical system. In 2013 beam propagation through an optical system with the two-adaptive-optics configuration and beam shaping is reported in a Ref. [16].

In the previous studies the design and operation of a new system based on a plastic fiber-bundle prism-coupled waveguide for the beam shaping are reported [17,18]. Although, as described in the following work a flat-top beam profile is generated using such a beam shaper [19,20], but in addition to the intensity distribution, the divergence of the output beam is also important in order to use in end-pumping arrangement of solid-state lasers. In this respect, the first aim of this article is to investigate the behavior of the output beam after propagation in the free space. The optic software VOB is utilized to simulate and describe the merits of this beam shaping system. Second goal is to compare the simulation and experimental results and give some precise information, which can be helpful in design and optimization of such systems.

2. Optical system description

The schematic diagram of the beam shaping experimental arrangement used in this investigation is shown in Fig. 1. In General, the experimental system with the exception of the CCD camera, which is removed, is similar to the previous one [20]. As can be seen, it consists of a light source illuminating the fiber-bundle, a prism beam shaping duct, a digital camera, and a PC. The output signal of the digital camera is sent to the PC via an interface cable and final data processing is accomplished by using the related software. In the optical fiber bundle design 12 individual plastic core fibers with lengths of about 60 cm are used for the illumination of the prism duct. The core, cladding and buffer jacket diameters of each fiber are 0.85 mm, 0.98 mm and 2.2 mm, respectively. In this design all fibers are placed side by side to form a liner cable in output and packed together to form a circular cross section to be used for the light illumination. The outer diameter of input circular is 8 mm, and the physical size of rectangular dimension is about 26.4 mm × 2.2 mm at the other end. A dome structure white light emitting diode (LED) operating under 3–6 V dc voltage is used in this experiment. A fixed voltage supply of 4.5 V is used in the results reported here. The glass prism duct used in this investigation has an input face with the dimension of 58 mm × 4.15 mm and exit face of about 4.15 mm × 4.15 mm with a total length of about 100 mm.

The light detector used after the second stage beam shaping to take the beam photographic shape and intensity of the prism duct is a digital camera (Canon, model Power Shot A 1000 IS). The CCD array of the digital camera has a dimension of 2736 (H) × 3648 (V) pixels. The digital output data of the available digital camera is in JPEG format, which cannot be processed directly. In the experiment, an arrangement is made to convert JPEG files to MATLAB m-files, which can be easily manipulated by the MATLAB programs.

3. Experimental results

Experimental results of the variation of the output beam shape and converted intensity profiles for the beam shaping are presented in this section. As shown in Fig. 1, the beam shaping proceeding has been done by using two optical elements. First, a fiber-bundle that changes a beam with a circular cross section (radius of about 8 mm) into a beam with a rectangular cross section of about 26.4 mm × 2.2 mm. Second, the fiber-bundle output beam is condensed into a beam in square shape with a dimension of about 4.15 mm × 4.15 mm by a prism duct. In this study, the variation of the duct output beam shape and intensity profiles in the second stage of beam shaping process are investigated by using the images, which are taken by the digital camera system.

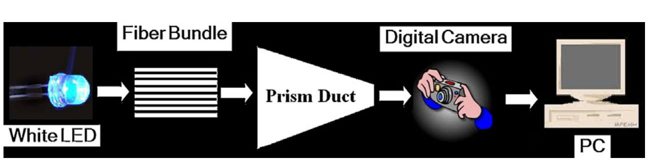

Fig. 1. Block diagram of the experimental arrangement for the beam shaping.

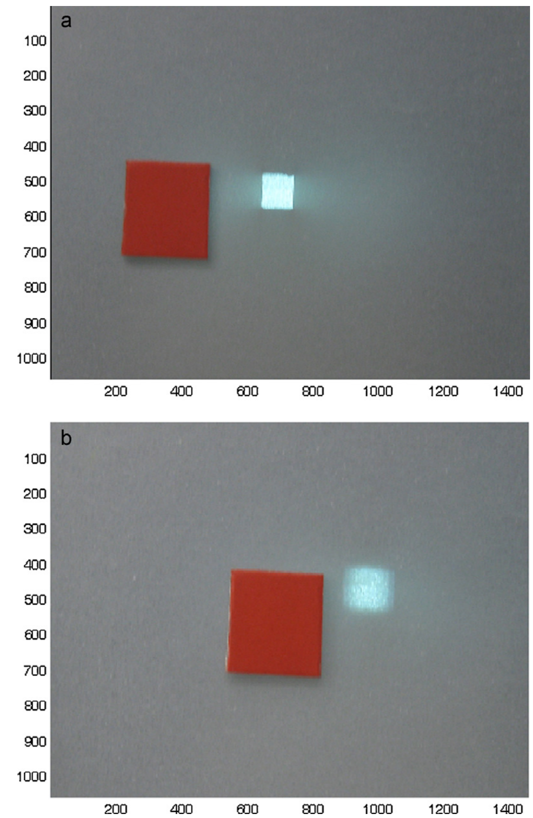

Fig. 2. Digital camera image of the prism duct output at: (a) exit face; and (b) 4 mm distance.

To measure the size of the obtained beam images, a specific object with a known dimension is used as a reference. In order to monitor the beam shape, the transmitted light is illuminated on a sheet of paper. The illuminated beam cross section with the reference object is simultaneously pictured at different axial distances by using the digital camera. Here axial distance from the prism duct exit face to the digital camera lens is considered as z. Some images for the z variation of 0–4 mm are taken and saved as JPEG-format files. The captured images at $z = 0$ and $z = 4$ mm are displayed in Fig. 2(a) and (b), respectively. As it can be seen from images of in Fig. 2, there is the pictured image of the reference object in the left side of both images. It must be pointed that in images of Fig. 2 the horizontal axis shows the x-pixel arrays (1450 pixels) and the vertical axis shows the y-pixel arrays (1057 pixels). Fig. 2(a) shows the picture of the duct output beam just at the prism exit face. As it can be seen in Fig. 2(a) the output beam has a square shape with a size of about 4.15 mm × 4.15 mm. Fig. 2(b) shows the picture of the prism output beam at 4 mm distance from the exit face. Due to the divergence of the refracted beam the dimension of the output image shown in Fig. 2(b) is considerably larger than that of shown in Fig. 2(a).Here it has a rectangular shape with a dimension of about 5.5 mm × 4.5 mm.

As shown in Fig. 2, the prism output beam picture after propagation can be considered as a rectangular with a width and a height in