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Design and Operation of a Simple Beam Shaping System

[1]A. Haghighatzadeh, [2]H. Golnabi and [1]M. Shakouri
[1]Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, P.O. Box 14665-678, Tehran, Iran
[2]Institute of Water and Energy, Sharif University of Technology, P.O. Box 11155-8639, Tehran, Iran

Abstract: Design and performance of a beam shaping device based on a simple flexible plastic fiber-bundle stripe and a prism duct is described in this study. Such a system offers practical means to modify and change the output beam shape and also provides quantitative information concerning the transmitted power. It is possible to measure transmitted power signal by using a precise photodetector and also analyze beam images taken by a digital camera. The photograph picture of the illuminating LED beam just at its output point shows a circular shape with a radius of about 4 mm and the fiber-bundle output beam is rectangular shape with a dimension of 22.5×2 mm. A regular duct is tested in this study and the optimum condition for the maximum power transmission and best image quality is reported in this study. The transmitted output power signals by the fiber bundle and prism duct are measured as a function of distance from each optical element. Using this system at the first beam shaping stage, the input circular beam with a diameter of about 10 mm is changed into a rectangular beam shape of 22×2 mm width and height by the fiber bundle. The power signal efficiency of about 64.86% is obtained for this stage. The rectangular beam is then changed into a square beam shape of 5 mm width at the second stage and the overall power signal efficiency of about 6.48% is obtained for this design.

Key words: Transmission, beam, shape, fiber, prism

INTRODUCTION

Beam shaping techniques can result in beam cross section modification in addition to an improvement in the beam quality in terms of coherence and other beam parameters. Different optical elements and optical devices such as collimators and beam expanders can be used for this purpose. Many attempts have been made to improve the beam quality of light sources, in particular laser sources by using linear and non-linear optical materials. In addition to the experiments different calculations have been done to describe the characteristics of the modified beam. In a recent study numerical calculation concerning the use of a concave-convex lens for shaping axisymmetric laser beams is reported by Liu *et al*. (2008).

Focus shaping of cylindrically polarized vortex beams by a high numerical-aperture lens is given in a reference (Rao *et al*., 2009). Interferometry is another means to change the beam shape and a nonlinear filtering and beam shaping with a nonlinear polarization interferometer is described by Kourtev *et al*. (2008). Hao and Leger (2008) discussed a numerical aperture invariant focus shaping using spirally polarized beams. By using holography technique some beam modification has been accomplished and a study titled as holographic shaping of generalized self-reconstructing light beams is reported as a results of such studies (Thomson and Courtial, 2008).

In another study, pattern generation using axicon lens beam shaping in two-photon polymerization is reported by Bhuian *et al.* (2007). In fiber optic applications small lenses have been used for the beam shaping. For instance, in a report laser diode beam shaping with GRIN lenses using the twisted beam approach and its application in pumping of a solid-state laser is explained by Johansson *et al*. (2007). Grating is another optical element that is used for the laser beam shaping. For example, the result of such studies is indicated in a reported by Kajava *et al*. (2006) in which the flat-top profile of an Excimer-laser beam was generated by using beam-splitter gratings. Filtering is also used for the beam shaping and in a reported by Ibáñez-López *et al*. (2007); they described construction and the manufacture of pupil filters for 3D beam shaping.

Laser beam shaping as mentioned is an important issue in laser application and in laser material processing. In a report the beam concentration and homogenization for high power laser diode bar is described by Fan *et al*. (2008). There are some reports on the high power laser

Corresponding Author: Azadeh Haghighatzadeh, Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, P.O. Box 14665-678, Tehran, Iran Tel: +982166164652 Fax: +982166164651

beam shaping issue. For example, in a recent report high-power laser beam shaping by inseparable two-dimensional binary-phase gratings for surface modification of stamping dies is reported by Li *et al.* (2008). In another study by Boyko *et al.* (2005), an adaptive shaping of a focused intense laser beam into a doughnut mode is described in detail. Passilly *et al.* (2004) reported the one-dimensional laser beam shaping using an adjustable binary diffractive optical element is presented.

From application point of view some studies have focused on the effect of beam shape in different applications. For example, a study by Sanner *et al.* (2007) described the direct ultrafast laser micro-structuring of materials using programmable beam shaping. Variation of the beam shape in different media has been a great concern in the practical applications. For instance, in atmospheric propagation a report by Eyyuboğlu *et al.* (2006) explained the convergence of general beams into Gaussian intensity profiles after propagation in the turbulent atmosphere. Design guidelines and characteristics of beam-shaping microstructure optical fibers are also presented in a report by Lu *et al.* (2006). In recent years solid state lasers have become more important and development of high-power diode laser stacks has opened up an effective way to activate such materials. Using fiber-coupled light sources and beam shaping methods introduced a variety of optical pumping schemes. The goal has been here to develop a beam shaping device based on optical fiber waveguides for effective source beam transfer and modification. Several tasks such as beam modification, image taking and processing are conceivable using the reported system.

MATERIALS AND METHODS

Design and construction of the fiber bundle, fiber holders and mechanical parts required for the experimental set up are accomplished in Institute of Water and Energy of the Sharif University of Technology. Measurements and performance testing of the reported experiment were conducted in Sharif University of Technology and in part in Islamic Azad University of Iran for the period of 2007-2009. Experimental arrangement for testing the beam shaping device is shown in Fig. 1. As can be seen, it includes a light source illuminating on the fiber bundle, a prism beam shaping duct, a large size photodetector and a digital multimeter. A digital camera is used to take the photographic pictures at different stages of beam shaping. In the fiber bundle design about ten fibers are used side-by-side to form a wave guide stripe. As mentioned the arrangement for the fiber bundle is stripe type made of five double fibers (10 fibers) beside each

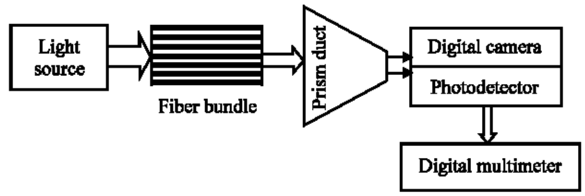

Fig. 1: Block diagram for the experimental arrangement

others having 65 cm length. In this layout all double fibers are placed side by side to form the linear cable arrangement in output and packed together in a circular form to be used for the light source illumination. The physical size of the input circle is about 6 mm in diameter and the output cable forms a rectangular physical dimension of about 2.2×22.2 mm. The entrance and exit faces of the fibers are polished roughly to reduce the reflection loss. However, the present design uses no AR coating for fiber faces and by using AR coating on involved interfaces the reflection losses can be reduced to a great extent.

The prism duct used in this investigation has a length of about 100 mm made out of regular glass plate. The entrance cross section of the prism is about 57×4 mm and the exit face of the prism has a cross section of 4×4 mm. The entrance and exit faces of the prism duct is polished roughly to reduce the reflection loss. However, in the fabrication process of the present prism design no AR coating is used for crucial interfaces and by using such coating and better polishing process the reflection losses can be reduced considerably, which is our next goal.

A photodetector in photovoltaic mode is used for signal measurements in this experiment. It is designed for the exclusive use with the large size optical beams. It uses a silicon photodiode as the light sensor with the large effective area of 60×60 mm. The electric output signal of this photodetector is connected to a digital voltmeter by a coaxial cable. A digital multimeter is used for the output voltage reading and data recording (±0.1 mV precision). More details about the digital multimeter interfacing to PCS and related programs can be found in the earlier study (Golnabi and Azimi, 2008). Information concerning the precise image processing and beam profile and image transfer study in multimode optical fiber coupling reported by Golnabi (2006) and Asadpour and Golnabi (2008).

It is possible to use the coherent and non-coherent light sources for the fiber bundle illumination and power measurements. The amount of the transmitted light and the quality of the images strongly depends on the lighting techniques as indicated in given reference (Kopparapu, 2006). For the reported results a white LED is used in these experiments in direct illumination arrangement of the fiber bundle. The LED operates at visible wavelength range with a dc voltage supply of about 4 V. The physical dimension of the LED is about 10 mm in diameter with the conventional dome optic coupling in front. To vary the launching power the supply voltage applied to the light source is changed for a suitable range. For the LED operation the appropriate supply voltage is from 3-6.5 V. However, throughout the experiment all the signal measurements are compared for a similar input launching power corresponding to the same voltage supply of 4 V.

In order to reduce the stray light effect in the power measurements a black cover is prepared for the experimental set up during the signal measurements. A large size photodetector as described converts the photo signal to the electric one for voltage measurements. In the first study, the light transmittance and beam analysis are performed for the white LED source. The fill factor depends on the illumination area of the fiber bundle and the overall numerical aperture of the bundle. For the circular cross section including the protective sleeves the effective illumination area of fiber bundle is confined to a radius of about 3 mm. Thus, the effective illuminated area of the fiber bundle (fiber cores) is much less than that of the total bundle area. However, the fill factor can be improved by using better fibers and fiber arrangements in cable construction in order to improve the fill factor and source-fiber coupling efficiency.

RESULTS

The goal here has been to monitor the power signal and image information from the fiber bundle pumping of a simple prism duct. A large size photodetector as described converts the photo signal to the electric one for voltage measurements. In order to reduce the stray light effect in the power measurements a black cover is prepared for the experimental set up during the signal measurements. In the first study, the light transmittance and beam analysis are performed for the white LED source.

In this study, the variation of the beam shape is investigated by using the images taken with the digital camera. To monitor the beam shape; the transmitted light is illuminated on a screen (millimetric paper) and by using a digital camera the beam cross section is photographed. Figure 2 shows the photograph picture of the LED beam just at its output point. As can be seen the output beam of such LED is almost circular with a diameter of about 10 mm at that distance. As mentioned the physical dimension of the LED optic dome is also about 10 mm in diameter.

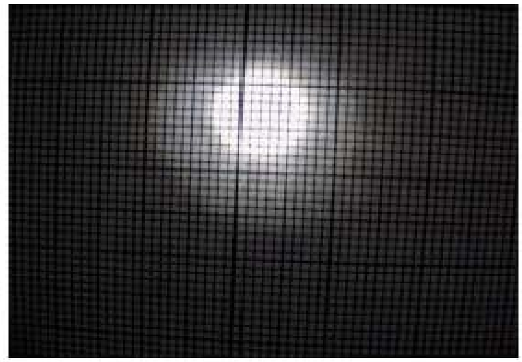

Fig. 2: Beam image for the white LED light source at its output point

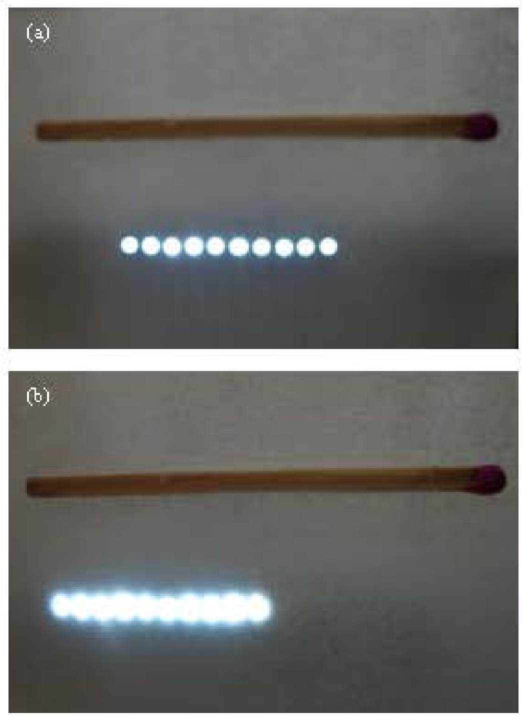

Fig. 3: Fiber-Bundle output light images, (a) at fiber tip and (b) image at z = 4 mm from fiber

Similar experiments are repeated when the image plane is about 1-5 mm from the LED light source. Obtained pictures show that output beam of such LED is almost circular in shape at all distances, but shows an increase in image diameter as a function of propagation distance. As a result the LED beam cross section is enlarged due to divergence effect with the propagation distance.

In a similar way pictures of the fiber-bundle output beam is obtained and the photographs showing such images are described here. Figure 3a shows the fiber-bundle output light picture at fiber tip. Each spot on the picture shows the output of the fiber bundle, which is all circular in shape and almost similar in cross section and brightness in the presented picture. The numbers of light spots are corresponding to the number of the illumination fibers in the cable (10 fibers) and the black area between the spots is due to the non-transparent protective sleeve jacket of each fiber. As mentioned the physical dimension of the linear fiber bundle is about 22.2×2.2 mm and the output illumination area at the fiber tip of the cable theoretically is about 20.4×0.85 mm. By considering the experimental result of Fig. 3, the output cross section picture shows an overall dimension of about 22.5×1.7 mm, which is in agreement with the estimated value. As can be shown in Fig. 3, a specified object with known dimension is pictured simultaneously as a reference in order to scale the obtained beam images. However, as can be seen in Fig. 3a, due to divergence the diameters of the spots in the picture are considerably larger than the physical fiber core diameter (0.850 mm). As can be shown in Fig. 3a, beam shaping is accomplished by the fiber bundle where the circular cross section of about 10 mm in diameter is changed into a linear rectangular cross section of about 22.5×1.7 mm. By monitoring the beam cross section on a screen it is noticed that the fiber bundle output is diverging considerably by increasing the propagation distance.

In Fig. 3b, the photographed picture at a distance of about 4 mm from the fiber bundle tip is presented. As can be seen in Fig. 3a for 1 mm distance, the overall cross section is in a rectangular shape with a dimension of about 22.5 mm width and 1.7 mm height. In Fig. 3b, the picture image of the fiber-bundle output beam at 4 mm distance is shown. The rectangular shape light picture shows a dimension of about 25 mm width and 3 mm in height. Comparing the pictures shown in Fig. 3a and b, it is noted that due to the divergence effect the beam cross section is enlarged by increasing the propagation distance to about 4 mm. The black area between the bright spots noted in Fig. 3a disappear in Fig. 3b and a bright stripe type output beam image is noticed.

Finally, power measurements and beam analysis are performed for the prism duct at the second stage of beam shaping process. Figure 4a shows the picture of the prism output beam signal as at exit face. As can be shown in Fig. 4a the output beam has a square shape with a dimension of 4×4 mm. Figure 4b shows the picture of the prism output beam at 4 mm distance. The output beam shows a similar square image picture as shown in Fig. 4a. However, due to beam divergence the output image is enlarged slightly to a dimension of about 5×5 mm.

Using the millimetric scale on the paper the diameter of the beam image shown in Fig. 2 is determined for

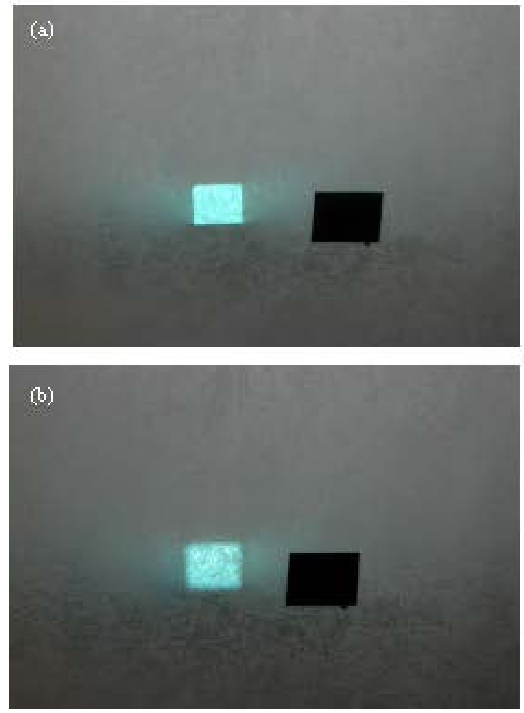

Fig. 4: Pictures of the prism output, (a) at exit face and (b) picture at 4 mm distance

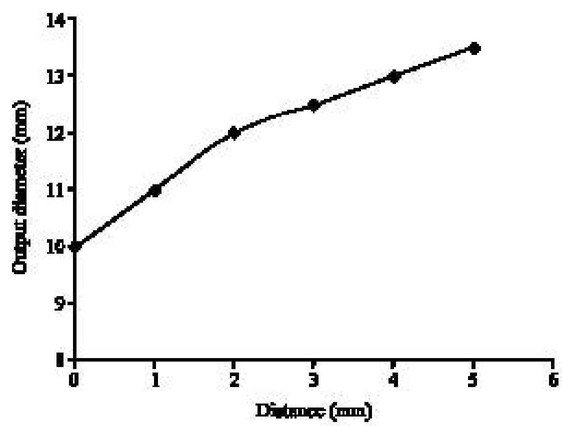

Fig. 5: LED beam diameter variation as a function of distance

various distances. As shown in Fig. 2, the LED beam image can be considered as a circle with a diameter of about 10 mm. In Fig. 5, the LED output beam diameter variation as a function of propagation distance from the LED source is presented. The measured diameter values as shown in Fig. 5 are increasing by increasing the distance from the source. For example, for 1 mm distance the beam diameter is about 11 mm while it increases to about 13.5 mm at 5 mm distance.

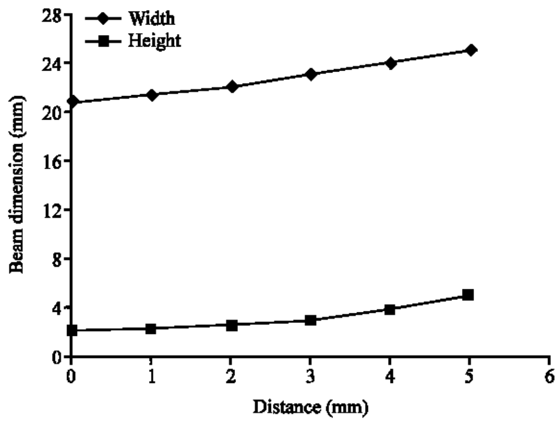

Fig. 6: Fiber bundle beam dimension variation as a function of distance

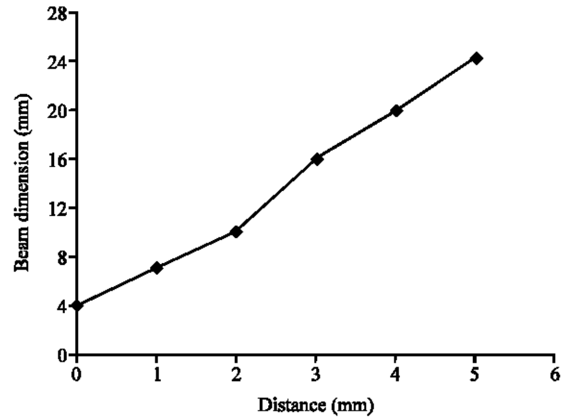

Fig. 7: Prism duct beam area variation as a function of distance

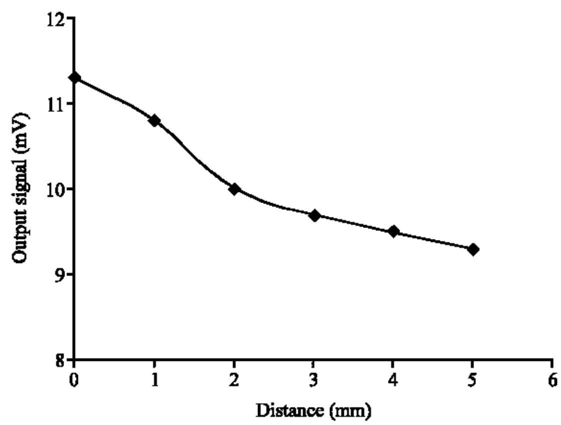

Fig. 8: Prism output beam signal variation as a function of distance

As shown in Fig. 3, the fiber bundle output beam image can be approximated as a rectangle with a width of W and height of H. In Fig. 6, the fiber bundle output beam dimension concerning W and H as a function of distance from the fiber bundle tip are presented. Using a reference image in the same figure the beam image size is determined carefully and shown in Fig. 6. The measured values as shown in Fig. 6 are increasing by increasing the distance from the fiber bundle tip. For example, for 1 mm distance the width value (W) is about 22 mm, while it increases to about 25 at 5 mm distance. Similar beam size variation for the height value (H) is noted in Fig. 6 and at 1 mm distance the H value is about 2 mm, while it increases to about 5 mm at a 5 mm distance. Such investigation suggests that for optimum source-fiber pump delivery the fiber output beam should be used just after the fiber bundle tip with the minimum divergence.

By comparing the results shown in Fig. 6 for beam width and height it is noted that due to the mentioned divergence effect the beam cross section is enlarged further by increasing the propagation distance. Comparing the increase rates for both directions it is concluded that the beam expansion percentage in height is relatively larger than in the beam width. Consequently, the aspect ratio (height to width) of the beam picture is not a fixed value and varies with the light propagation distance.

By using the reference image in Fig. 4 the actual size of the output beam is determined. As shown in Fig. 4, the prism duct beam image can be considered as a square with a size of about 4 mm. In Fig. 7, variation of the prism output beam area as a function of propagation distance from the prism exit face is plotted. The measured area value as shown in Fig. 7 is increasing by increasing the distance from the prism. For example, for 1 mm distance the beam area is about 16 mm^2, while it increases to about 26 mm^2 at a 5 mm distance.

In the last experiment, the output beam signal power of the fiber bundle and prism duct are investigated and typical results for the prism are shown in Fig. 8. The measured output signal is plotted as a function of the propagation distance. As can be seen the output signal at the prism exit face is about 11.3 mV while it drops to about 9.3 mV at a distance of about 5 mm. As can be seen in Fig. 8, as expected such power drop is not linear with the propagation distance. Such investigation suggests that for pumping purpose the pump light should be used just after the prism exit face for the optimum beam coupling.

Considering the power signal conversion at LED supply voltages of 4 V, the net output power signal of the transmitted light just after the LED is about 166.8 mV, while the Noise Equivalent Power (NEP) with the source light off in blackened area is around 0.3 mV. At the same LED supply voltages of 4 V and input light, the output power signal of the transmitted light just after the fiber bundle is about 110.8, while the Noise Equivalent Power (NEP) with the source light off is about 0.2 mV. At the same input light power and the experimental condition, output power of the transmitted light just after the prism as can be shown in Fig. 8 is about 11.3 mV while the suppressed Noise Equivalent Power (NEP) with the source light off here is about 0.1 mV.

DISCUSSION

The initial goal was to introduce a simple and effective design for the beam shaping operation and analysis, which is fulfilled in this experiment. Obtained results verified that such beam shaping and power analysis are possible with the proposed experimental set up. As described in result section, beam shaping from a circular to a rectangular and then to a square shape is accomplished successfully by using this experimental technique. The input circular beam with a diameter of about 10 mm is changed into a rectangular beam shape of 22×17 mm width and height and the power signal efficiency of 64.86% at the first beam shaping stage. At the second beam shaping stage, the rectangular beam is changed into a square beam shape of 4 mm width and an overall power signal efficiency of 6.48% is obtained for the present design. Considering the given numbers, the efficiency for the first stage is relatively good but low conversion efficiency for the second stage needs more improvements. One reason is that we had only one prism duct available for the present experiment. For example, the 100 mm length is too long for such experiment and power loss could be reduced significantly by replacing or modifying such an optical element.

Comparing the overall efficiency with some other beam shaping results the conversion efficiency reported here for the initial test is a little lower than the other results. Therefore, like all the experiments of this type that high efficiencies are desired, the overall conversion efficiency for the output beam needs further improvements. The reasons for such lower power efficiency together with possible solutions will be given in the conclusion part. Considering the presented discussion, our future experiments and efforts will focus on resolving some described experimental issues and limitations in order to reduce optical losses, which ultimately lead to improving system efficiency.

CONCLUSION

In many area of light power delivery and image acquisition systems the beam shaping process is required to obtain a better beam quality or to produce a more intense light beam. A general-purpose beam shaping system with its preliminary results was described here that can be used for such operations. The present design with usual improvements can be used for the side pumping arrangement, which requires a rectangular beam shape for the solid laser bar. The pumping beam cross section out of the two-dimensional arrays is usually larger than the size of the laser rod, which results in an inefficient light coupling. To condense the beam size to match the rod cross section the presented design in combination with a lens duct system (Golnabi, 2003, 2004) can be really effective in the end-pumping configuration.

As described the purpose of the initial reported experiment was to introduce the design for beam shaping operations. However, conversion efficiency can be improved considerably by considering the following crucial points.

- The fill factor depends on the illumination area of the fiber bundle and the overall numerical aperture of the bundle. For the circular cross section including the protective sleeves the effective illumination area is confined to a small are of the fiber cores. One area of improvement is to increase the fill factor and LED- fiber bundle coupling efficiency
- Use plastic or glass optical fibers with lower transmission losses
- Use a more efficient prism duct. Such improvement can be made both by considering shape, size and prism materials
- By using a better polishing process and AR coating of all surfaces at interfaces including fibers and prism the power conversion efficiency can be improved considerably

One goal of future experiments is to imply such changes to the present system and see the final effects on the experimental results.

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