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Fiber Output Beam Shape Study Using Imaging Technique

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Abstract: In this study the output beam profiles of the single mode and multimode optical fibers are investigated by the cross sectional imaging technique. Different experiments are performed for the single mode and multimode fibers and the captured images are compared. The relative near field intensity distribution and their relative changes with respect to the distance is examined and some fiber parameters are obtained. A similar pattern in the real-time image is observed for the two type fibers and major differences are discussed. Using this method it is possible to determine the numerical aperture of the illuminated fiber, which is about 0.22 for the tested fiber. The effect of coherency of the light source on image formation is also investigated and speckle pattern formation in the case of coherence laser light source is discussed.

Key words: Laser, fiber, image, intensity distribution, beam shape

INTRODUCTION

Beam shape study is a non-contact and effective method for obtaining illumination source characteristics, whether it is active like a laser output or passive like an optical device or an optical fiber. Fibers are now efficient optical wave guides and are used as transmitting media for the power and information. Image transmission investigation is an effective method for probing spatial light information transmitted down an optical fiber which is discussed in many studies (Heacox, 1987; Yariv, 1976; Tai, 1983; Naulleau *et al.*, 1996). Power transmission is mainly used in industrial applications such as industrial machines for cutting, welding, drilling and smoothing. In these applications usually a low loss, large core, silica fiber is used to carry the high power laser beam to the target under operation. Depending on operation type there is a threshold laser power for an effective laser material processing tasks (Su *et al.*, 1992; Yan *et al.*, 2008).

Another optical power transmission necessity is in laser surgeries and clinical laser treatments (Fujii *et al.*, 1984). In practice, medical applications such as these are the most challenging areas for the light beam shape investigation because the dept and area of the tiny cuts in the body cells are crucial and must be accounted for in an optimum laser treatment. Besides, the necessity for an assigned output beam shape in a medical procedures and treatments enforce us to study the fiber waveguide roles in maintaining the characteristics of the launched beam. For example bending, dispersing and beam aberrations by the optical fiber can cause the deformation in beam shape or the input light profile.

In telecommunication systems information mostly transmitted via temporal modulation of light and the bandwidth of transmission is limited to the inter-modal dispersion. Methods to exploit modal dispersion and use them as means for different communication channels is called MIMO or multiple input multiple output and is a challenging task, which is presented in several studies (Lenz *et al.*, 2004; Shah *et al.*, 2005; Rick *et al.*, 2004; Raddatz *et al.*, 1998; Windover *et al.*, 2004). One MIMO method is Spatial Division Multiplexing and it highly depend on spatial distribution of input light and the study of optical fiber output beam shape will be helpful on achieving certain fiber output and utilize them as different communication channels (Murshid and Chakravarty, 2008; Jansen *et al.*, 2008; Stoddart and White, 2009).

Transmitted information depend on spatial optical distribution, for example if we have a narrow laser beam and lunch it to the center part of the core of a multimode fiber the bandwidth is different from offset lunching techniques as described by Tsekrekos *et al.* (2007). As stated in the previous studies, from the output pattern the location of lunched beam on the fiber front face by such an image analysis can be guessed. Beam profile and image transfer study in the fiber coupling is reported recently

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(Asadpour and Golnabi, 2008). The changes in output beam power and intensity profile are investigated in that study and important issues such as the role of the air-gap in fiber coupling and core diameters are described. In this study we evaluated and investigated the intensity profile of the output beams for different single fibers for different light sources. We discuss how single and multi-mode fiber wave guides can be treated by imaging techniques. The goal here is to show how the captured images of output beams can lead to important optical information concerning the obtained images and drawn conclusions. It is also, desired to compare the output images observed by single and multi-mode fibers and relate those to new optical results. Another aim of this research is to investigate the role of coherency of illumination sources in image formation and intensity profiles.

MATERIALS AND METHODS

Design and construction of the different parts and 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 for the period of 2007-2009. The experimental set up used in this investigation is shown in Fig. 1. As shown a light source illuminates the fiber front face and the output light is projected on a CCD camera. The output signal of the CCD camera is transmitted to a PC via an interface module. Using a CCD camera is a useful method and image evaluation for synchronized laser scanning systems (Golnabi, 1999) and precise CCD image analysis for planar laser induced fluorescence experiments using CCD cameras are given in literature (Golnabi, 2006). For more information concerning CCD cameras, efficient use of CCD cameras in image capturing and image evaluation. The real-time framed images are grabbed by the proper interfacing program controller (Capture card and Pixel View controller) and transmitted to the PC for further correction and possible processing.

We have used different kinds of light sources, an incandescent white lamp (12V voltage supply) and a white power LED (3.5V-2.5 mA power supply) are used as incoherent light sources and a 3 mW diode laser (12V voltage supply) is used as a coherent light source. For a better comparison in all the reported results care is taken to keep the light source supply voltages constant during the experiments. The fibers tested in this experiment are 10 m, step-index, single mode and graded-index multimode silicon patch cords (IEEE 802.3 standard, OM1), used in telecommunication Gigabyte Ethernet optical links. Although, losses for these fibers in 1550 and 1310 nm wavelengths are much lower than tested wavelength region but for our experiment the optical loss is not the main concern.

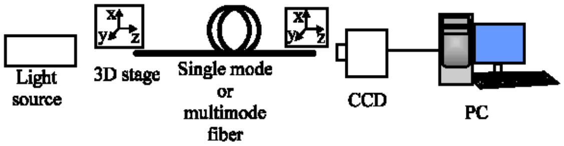

Fig. 1: Experimental setup including the light source CCD and PC

RESULTS

In the first experiment the single mode fiber is tested and the captured real-time image is investigated. Figure 2 shows the output beam image of the single mode fiber for white LED source, where the source light is lunched on the fiber by a lens of 1 mm focal length. The fiber output beam is then projected on the CCD camera without using any lens or optical devices. In Fig. 2, picture shows the real-time image of the fiber output beam in RGB format (Red highest intensity, Green less intensity and Blue the lowest intensity) and the image spot is generally bigger than the fiber core diameter. The vertical axis in the graph shows the Y-pixels (240 pixels) and the horizontal axis shows the X-pixel arrays (320 pixels). The recorded intensity area on CCD is the exact projection of output beam of the optical fiber and can vary significantly by the fiber end face distance to the CCD, distribution of source light, lunching condition and type of fiber wave guide.

As can be seen from image of Fig. 2, the images are shown in RGB color format and concentric circular images around a central disk are obtained in this case. A careful observation of the image circles shows that the color of

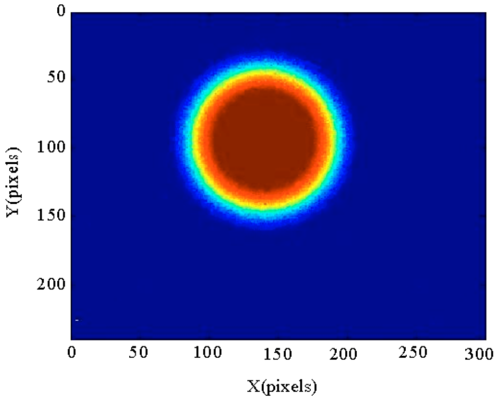

Fig. 2: Image of the single mode fiber output at 5 mm from fiber end and incoherent illumination

the rings around the brown center disk is changing from red to yellow, green and light blue, respectively. The dark blue around the real circle images show the background image of stray light with the minimum intensity in the color map image. Considering the order of the colors in the color map it is clear that much of the imaged light is as a result of illumination from the fiber core part as indicated by brown color in Fig. 2. The next circle in image of Fig. 2 shown with red color shows a lower light intensity, which shows drop of light intensity and a similar reduction in light intensity is observed as we move to outer circles in image of Fig. 2. From color map of circular images it is suggested that the output intensity distribution is nearly a Gaussian beam.

In terms of mode analysis capability, the maximum bandwidth for detecting individual modes in an optical fiber is given by the following equation:

$$\Delta\lambda \ll \frac{\lambda}{2\pi\Delta nL} \quad (1)$$

where, in which λ is the wavelength of the light, Δn is the relative refractive index of the core and cladding and L is the length of the fiber. By coherent illumination we mean a light source which fulfill this condition and the other sources are addressed as incoherent. The main reason for using incoherent light sources is to avoid speckle pattern at the output and having a smooth profile, which makes the cross sectional imaging and profile analysis easier and more comparable.

In order to show image intensity profile the image data are stored in a buffer matrix (640×480) in the MATLAB program and such data are used for intensity profile representation. Figure 3 shows the intensity profiles at two different distances, which are a plot of the middle row of intensity image versus column number (X-pixels) of the buffered matrix. As shown in Fig. 3, by increasing the imaging distance there is not much change in the profile at the top of the curve and only it is widened and slight side lopes are beginning to form. We can see in Fig. 3 that the intensity profile is very similar to a Gaussian distribution for smaller distances and for the far field image gets closer to the hat-top distribution. Concerning the source light change, there is no difference between the white lamp and the power LED intensity image profile except the fact that overall maximum of intensity profile of the power LED is higher than that of white lamp.

In order to show more precisely the effect of distance variation on the intensity profile in Fig. 4 the envelope to the output beam of the single mode fiber at different distances is shown. To plot Fig. 4, beam radius is determined at each given distance and the slope is computed from the following equation:

$$S = \frac{R_2 - R_1}{D_2 - D_1} \quad (2)$$

where, S is the slope, R is the radius of the image circle at given points and D is the distance at the corresponding points. The value of computed slope as shown in Fig. 4, is about 9 pixel mm^{-1}. For small slopes the tangent function can be approximated by the sinus value of the angle, which defines the numerical aperture of the tested fiber. As explained using this method it is also, possible to determine the numerical aperture of the illuminated fiber. From calibration measurement 1 mm on the image taken by our CCD corresponds to about 20 pixels so the numerical aperture of this fiber obtained from Eq. 2 is approximately about 0.22.

In the second study similar experiments are performed for the multimode fiber. In Fig. 5 the real-time image of the

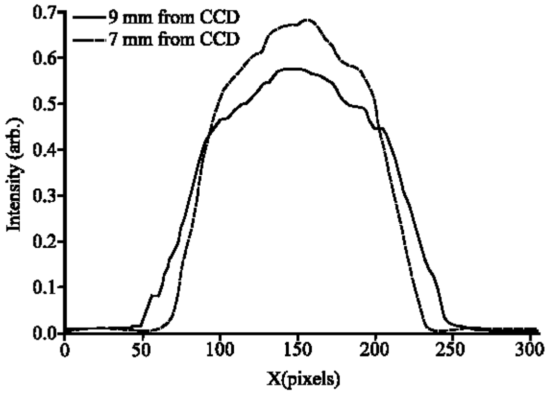

Fig. 3: Intensity profile of the single mode fiber at 7 and 9 mm distances from CCD

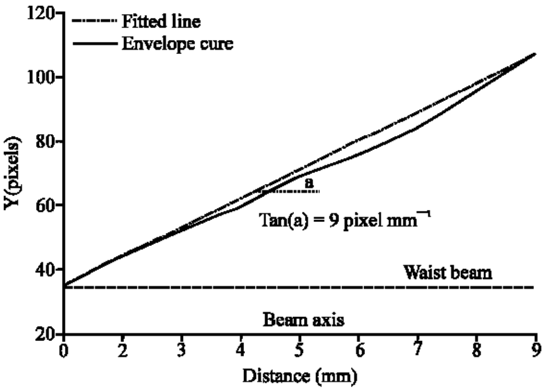

Fig. 4: The envelope of the output beam intensity curve at different distances from CCD

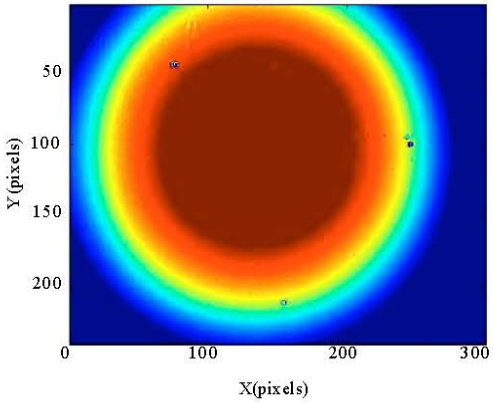

Fig. 5: Image of multimode fiber output at 5 mm from fiber end using incoherent illumination

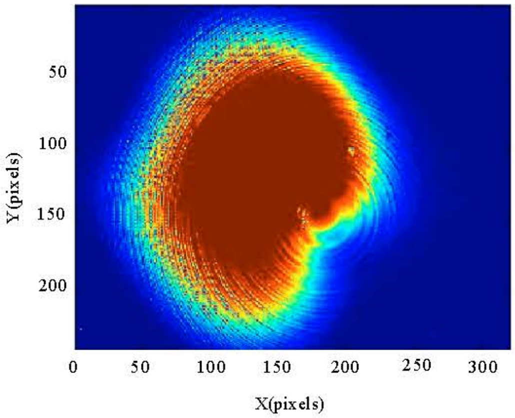

Fig. 7: Image of the single mode fiber at 10 mm from the fiber end and coherent illumination

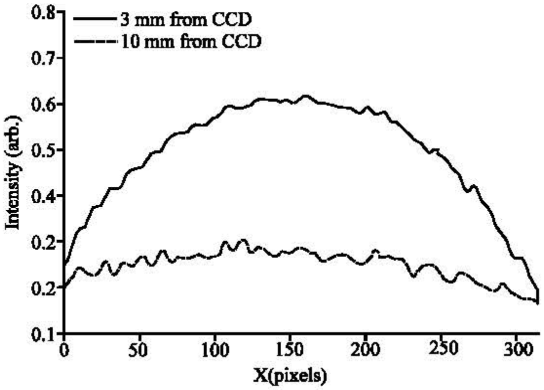

Fig. 6: Intensity profile at 3 and 10 mm distances of fiber from CCD

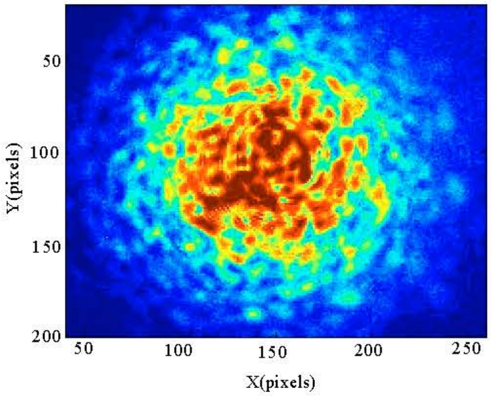

Fig. 8: Image of the multimode fiber at 5 mm from the fiber end and coherent illumination

output beam of the multimode fiber is shown. A similar pattern in image is observed with two major differences. First, the core size and as a result the illumination area of the multimode fiber is much bigger than that of single-mode (Fig. 2), which is clearly notable in Fig. 5. Comparing Fig. 5 with Fig. 2 for the single-mode fiber image clearly shows such a difference because of the larger core diameter of the multimode fiber. The second observation is that due to graded-index distribution of the index of refraction for multimode fiber the gradual drop of the image intensity is slightly different from that of single-mode fiber.

In Fig. 6 the two image intensity profiles of the output beams at 3 and 10 mm are compared. The vertical axis shows the beam intensity as a function of the X-pixels for the given distances. As can be seen in Fig. 6, the intensity distribution is approximately Gaussian in shape very similar to the near field image for the single-mode fiber (Fig. 3). However, the near far field image (10 mm distance) for the multimode fiber is approaching the flat-top function for the given pixel range of 0-300. Comparing the result of multimode with that of single-mode fiber it is noted that for both cases at near field case there is not much change in the profile by distancing and in general intensity distribution function looks like a Gaussian beam profile.

To see the effect of coherency on image formation in this study a coherent laser source is used for fiber illumination. Figure 7 shows the output of the single mode fiber, illuminated by a diode laser. As can be seen in Fig. 7, We don't have a smooth and clear spot in the image pattern. It seems the observed pattern is due to the interference effects. As can be seen in Fig. 7, a distortion is occurred in the output beam image due to the diffraction from output aperture. A clear picture of speckle pattern of the multimode fiber is shown in Fig. 8 for a distance of 5 mm . The speckle pattern occurs because of

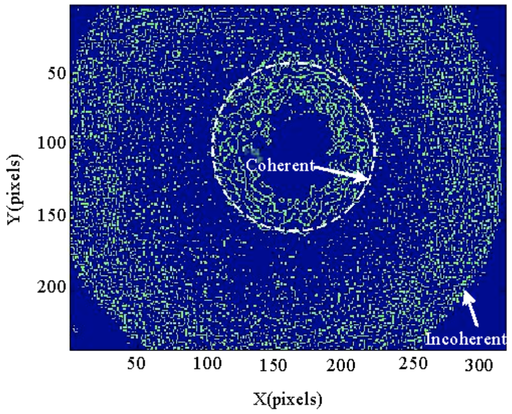

Fig. 9: Comparison of two images at 4 mm from fiber end for coherent and incoherent sources

the inter-modal interference that can cannot be predicted and formulated easily. However, one can use this phenomena of pattern change in designing of a sensor system. Due to static behavior of the speckle pattern this effect can be used in construction of fiber speckle sensors. As stated by Fang-Wen and Chen (2008) we can reduce the speckle pattern of a coherent source by using optical diffusers in the beam path.

For comparing the output of the multimode fiber, an edge detection method is applied to the output image of coherent and incoherent illumination cases. The edge detection is a method for finding the changes in intensity or the border of a spatial optical phenomenon recorded in an image. The color map of intensity images in two pictures have different effective areas and one can find this area by edge detection method that is provided by the image processing tool of Matlab software. This method enable us to compare the area and patterns of the output beams in a single image, which is applied to plot Fig. 9. Two edge images of coherent and incoherent cases are pasted together and shown in Fig. 9. As indicated in the image picture of Fig. 9, the center portion of the image is related to the coherent source image while the larger pattern shows the image formation for the incoherent light source from the same fiber. For a better comparison a size calibration technique is also used. As shown in Fig. 9, the image area of the coherent light source from the fiber output beam corresponds to a pixel area of about 100×100 while for the incoherent illumination of a similar fiber guide the image area is about 300×300 pixels. Edge detection provides a uniform dot diagram for the incoherent light image, while it shows separate regions for the speckle image of the coherent light. As shown in Fig. 9, profile intensity for incoherent light image is distributed as dots on a large image area (300×300) while the central portion of the Fig. 9 shows speckle regions corresponding to the coherent image region produced by interference effect.

DISCUSSION

Generation of the incoherent light beams is simple in design and usually inexpensive, which makes them suitable for many applications. However, for more precise measurements and high power deliveries coherent laser light sources are used in industries and medical procedures. Incoherent light sources can be considered as very good illumination means of fibers in order to investigate the output beam cross sectional imaging and profile. Using an incoherent light for fiber illumination, the differences between single mode and multimode fibers output beams can be recognized in terms of the spot widths and delivered intensity. For a single mode fiber beam transmission the output spot is much smaller and sharper than that of a multimode fiber. The output beam of such fibers maintains its shape and experiences a lower divergence, while for multimode fibers the output beam is enlarged considerably with a higher divergence effect. As a result, in industrial cases, single mode fibers are more suitable for applications such as laser cutting and drilling while multimode fibers can be used in welding and etching, which require higher delivery intensity. In medical procedures and laser treatments multimode fibers are generally better for skin illuminations and scar therapies, while single mode fibers are extensively used in more delicate treatments such as cell burning and cutting of the flesh.

The observed output beam shows a speckle pattern, which complicates the beam shape analysis. To reduce speckle size optical diffusers can be used in input to form spatial incoherent light and make the cross sectional imaging easier. Image of output beam of a single mode fibers shows a spot, but the small aperture affects the output beam and the output is not necessarily circular, thus for small cuts, burning small hole and single cell illuminations this effect influencing the beam shape must be bared in mind. The result of this study helps the image analysis of such transmission fibers for different purposes. Speckle profiles of multimode fibers is not a problem in laser healing of scars and skin therapies or even in cutting and welding in industrial applications. However, in microscopic operations using the output beam of a fiber line it should be noted that the illumination is not very smooth and uniform in intensity.

The results of the incoherent cross sectional imaging and profile imaging used in this study are in support of the results obtained by other methods. For example results for the near field output power distribution (NFOPD) investigations of fiber optics (Fujii *et al*., 1984). However, the incoherent profiling makes the task easier and precludes the computational averaging over illuminated area, which is done for the case of coherent laser illuminations. Moreover, the results obtained here are in agreement with the previous experimental output investigations (Asadpour and Golnabi, 2008) for the case of large core fibers. This study in addition to research of the Multi-Mode fibers expands the results to small core Single-Mode fibers, which are mostly used in telecommunication.

CONCLUSIONS

Fiber output beam study is a simple and effective method for investigating optical characteristics of the transmission line. Perfect or partial coherent sources cause some difficulties in output beam profile investigations and wavelength broadening is a method to avoid speckle irregularities. Image processing is a very useful tool for finding the spot size and speckle size and offers extra practical advantages. Present results show that even though coherent beams are widely used in industrial applications, but due to the dispersion and interference effects are not particularly appropriate for illumination of fibers to accomplish beam shape studies and for modal power investigations. The reported techniques can be useful in the study of spatial division multiplexing, which is used in telecommunication and also, can be used in the study of the effect of the beam size in medical skin and injury treatments.

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