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Degradation of beam quality and depolarization of the laser beam in a step-index multimode optical fiber

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Abstract

The characteristics of a laser beam are altered during propagating through large-core multimode optical fibers. The distribution of modes excited by the input laser beam is modified by means of mode coupling on transmission through the fiber, leading to the degradation of beam quality and the depolarization of the delivered beam. The relationship between the beam quality factor (M^2) of output beam from a large-core multimode fiber and the fiber length, as well as the relationship between the degree of polarization (V) of output beam from such a fiber and the fiber length, are introduced in this paper. When a laser beam was well launched into a large-core step-index multimode fiber, M^2 of the output beam was a compound tanh function of the fiber length. A linear polarization beam that well launched into such fiber suffered depolarization. The V of the output beam was an exponent function of fiber length. And the misalignment between beam axis and fiber axis made the beam quality degrade faster but made no difference of the utmost M^2 in the aligned and misaligned conditions. Also, the misalignment condition made the polarization of output beam degrade faster.

Keywords: Beam quality; Polarization; Large-core optical fiber

1. Introduction

Optical fibers are routinely used to deliver high-peak and/or high-average power laser in many industrial and surgical fields, including cutting material, percussion drilling, welding, marking and tissue ablation, etc. [1,2]. The flexibility and safety of a fiber-optic delivery system is especially beneficial when it is used in a complex three-dimensional work piece, where it is much easier to manipulate a compact fiber-coupled effector optics than to manipulate the work piece itself [3]. Large-core (0.2–1.5 mm) high NA (numerical aperture) step-index multimode silica fibers are used in flexible delivery systems for high-power lasers, such as Nd:YAG lasers, with great success [4]. However, such fibers will cause beam quality degradation and depolarization of the laser beam transmitting in it, and these degradations are dependent on the length, core diameter, type and material of the fiber, and so on [5,6].

Various characteristics of laser beam are demanded in different applications. For example, in industrial material processing, the laser beam quality factor M^2 (M^2 is a

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numerical expression of beam quality with 1 being a perfect Gaussian beam and higher values indicating poorer quality. The definition of M^2 will be introduced in Section 2) is demanded in the typical value range of 20–100, but in medical tissue ablation, M^2 is demanded $\leqslant 30$. It has been reported that in a fiber without sharp bends and with an input M^2 of 22 and a 90% core fill factor of the fiber core with the focused laser beam, a degradation factor is an exponent function of fiber diameter [3]. On the other hand, the curvature of fiber bend leads to beam quality degradation and depolarization of the laser; the value of the beam quality factor has a relationship with the bend radii [7].

The polarizing laser beam is used in some medical tissue diagnosis and desirable in certain sensors to raise the ratio of signal to noise. The partial polarized laser beam is required in some laser micro-machining. It was found that the guided light would be complete depolarized after transmission for a few cm in the fiber, due to core deformations and optical asymmetries. But further study revealed that the depolarization effect described above was overestimated. It was reported that linearly polarized light launched into a 3-m-long fiber was partially preserved [8].

However, a function that can quantitatively relate M^2 of the output beam with the fiber length, and/or can quantitatively relate the degree of polarization of the output beam with the fiber length, has never been developed. So it is significant to study the laser beam delivery performance of large-core silica fibers. So the performances for laser beam delivery of larger-core multimode fibers has been studied in our group and illuminated in this paper. Four series of experiments have been performed to measure M^2 and V of the output beam from such fibers. The quantitative function of M^2 and L (fiber length) and the quantitative function of V and L have been deduced. Maybe the functions can help one to foresee the beam quality and polarization of the delivered beam in such fibers, and hence to enable the delivery system to be designed to minimize beam quality degradation and depolarization of laser beams. The experimental results agree with the theoretical analyses.

2. Experiments

We carried out experimental studies of the characteristics of output laser beams from the large-core step-index multimode fused silica fiber by using the simple setups shown in Figs. 1 and 2. A single-mode ($M^2 = 1.002$), linear polarization ($V = 0.999$) continuous wave He–Ne ($\lambda = 632.8$ nm) laser with the power of 55 mW was used as a light source to measure M^2 and V of the output beam after propagation in such fibers. There were three kinds of large-core step-index multimode fused silica fibers: domestic optical fiber with 600 μm core diameter, 3M fiber with 400 μm core diameter and 3M fiber with 600 μm core diameter. The NA of the domestic fiber was 0.34 ± 0.01 and the NAs of the 3M fibers were all 0.40 ± 0.02. Every kind of fiber was cut into seven segments with lengths of 0.5, 1.0, 2.0, 3.0, 5.0, 10.0 and 22.0 m, respectively. So there were altogether 21 fiber samples. The fibers with lengths of 10.0 or 22.0 m were bent into circle loops with diameters of 1.5 m (it is considered that in this bend diameter, the effect of curvature can be ignored) and other fibers were all placed straight. The end surfaces of every fiber sample were prepared by mechanical polishing.

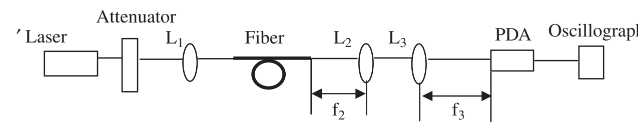

Fig. 1. Schematic setup for measuring the output beam quality factor M^2.

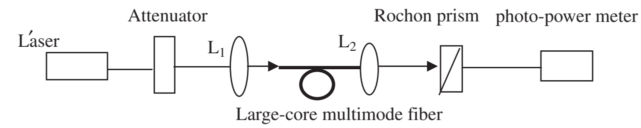

Fig. 2. Schematic setup for the measuring the degree of polarization.

In Fig. 1 a lens (L_1) was used to couple the laser beam to form a waist coincident with the size of entrance face of the fibers. The beam diameter was measured and defined with $1/e^2$ intensity contour [9]. The $1/e^2$ intensity contour beam diameter was adjusted to a maximum input spot diameter that is 86% of the fiber core diameter. A 100% fill of the fiber core diameter would be unsuitable because the focused laser beam intensity profile is not exactly top hat, this means that a small percentage of the power in the beam profile lies outside the measured $1/e^2$ diameter, which can cause excessive heating and catastrophic failure. For an 86% core fill factor, a transmission efficiency of between 80% and 90% was measured for all the fibers with different lengths. On the other hand, the incidence beam NA should be confined as $0.3\mathrm{NA}_{\mathrm{fiber}} \leqslant \mathrm{NA}_{\mathrm{beam}} \leqslant 0.9\mathrm{NA}_{\mathrm{fiber}}$. Too low an incidence NA can cause catastrophic bulk damage with a fiber at some distance from the input end and too high an incidence NA will cause power to be lost from the core into the cladding.

The output beam waist diameter is measured by imaging the exit end of a fiber onto a CCD. The lens L_2 ($f_2 = 30$ cm) collimated the beam exiting from the fiber and the lens L_3 ($f_3 = 100$ cm) focused the collimated beam onto CCD. The oscillograph connected to the CCD was to obtain an intensity profile and then the