A Customized Method for Recovery of Gaussian Beam Profile Emerging from Optical Fibers

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ABSTRACT

Loss of the Gaussian beam profile is frequently observed when lasers are combined with either classical or modern optics. This alteration in the beam profile affects the coherence length of the beam and produces an unfavorable output in laser applications. Poor cleaving of the optical fiber end face is the main cause of this problem, especially when cleaving is performed using low-precision equipment or nonstandard methods. This profile deformation prevents the intended output, which leads to an unanticipated leap in the laser beam profile from one Transverse Electromagnetic Mode (TEM) to another. In this work a method is proposed to mitigate this effect by attaching an optically flat glass piece to the end face of the fiber and using index matching gel. By guaranteeing a uniform distribution of the index matching gel, this technique enhances the consistency of the laser beam and successfully restores the Gaussian beam profile. Laboratory test results show that this technology is a viable substitute for conventional fiber-cleaving techniques and is rapid, easy, inexpensive, and dependable. While successful in controlled situations, other improvements, such as optical adhesives, are needed to achieve stable performance in settings that are prone to vibration.

Keywords-beam waist; laser beam; laser beam modes; normal distribution; optical fiber; power ratio

I. INTRODUCTION

Light Amplification by Stimulated Emission of Radiation (LASER) has proven to be one of the most reliable and precise bases for engineering applications. In these applications, the quality and modes of the laser beam play a vital role in obtaining the desired output. Any possible deficiency in the aforementioned parameters demands rigorous research work to be carried out in the field of laser beam profiling as well as the provision of solutions to overcome such a situation. Therefore, researchers have conducted studies on laser beams and their quality. Authors in [1] observed that doping the lasing medium with a nematic substance causes random lasing close to the resonance values. This behavior gives rise to a laser beam with extraordinary properties, which are regarded as random lasers, providing an equivalently extraordinary method for application-oriented random lasers. A method for beam cleaning during propagation through an optical fiber has been presented in [2]. As a result, an increase in the beam intensity at the fiber output was observed, which in turn improved the efficiency of the nonlinear images. Authors in [3] observed that the beam initially lost its circular symmetry. However, the adjustment of the polarization state of the beam using an optical setup is promising and can be used in applications, such as stimulated emission depletion microscopy, light trapping, and the processing of various materials. Authors in [4] used a green line laser, but found that the fundamental wavelength suffered from power scaling and poor beam quality. Upon investigation, it was revealed that the beam profile was elliptical compared to the expected circular profile. The use of an intracavity aperture after fine-tuning helped to recover the beam quality to a nearly circular profile. Several techniques to record the beam profile of a laser were presented in [5], and a comparison between a photoresistor and a photodiode was found to be in good agreement. A computer-aided laser-fiber optical beam designer for the basic Transverse Electromagnetic Mode (TEM_{00}) based on a 3D presentation was developed, which is normally a camera beam profile system. The simulated beam was tested for a complete analogy with Gaussian beam properties and characteristics [6]. Authors in [7] developed a customized laser-cutting device based on the Gaussian distribution of laser beam intensity. However, the device was tested for cutting wood pieces with thicknesses up to 2 mm. In [8], a Gaussian profile-based, positive gain dopant material was introduced and a Gaussian profile beam was attained, which was free from instability in the orthogonal to axis mode propagation (transverse). The dopant was added using the chemical deposition method. Laser operation was confirmed using a bidirectional pumped master oscillator power amplifier. Authors in [9] managed to tune the laser beam to its required profile. This method is based on the use of a multimode tapered fiber, which is pulled on after heating, thereby introducing irregularities in the fiber structure. A method based on an electronic circuit design to stabilize the output power of a laser diode was reported in [10]. This is because with an increase in the temperature of the laser diode, the output beam profile is disturbed. This disturbance is mainly due to changes occurring in the dimensions of the laser cavity, which causes other transverse modes to prevail in the basic TEM_{00} mode. Authors in [11] presented a laser beam multiplexing setup for three beams based on discrete optical components coated with special antireflection materials. The radiation input efficiency was determined by measuring the radiation intensity of the beams at the input of an optical fiber with the emerging radiation power from the optical fiber. This method provides guidelines for achieving high-power laser beams using low-power lasers. Experiments on beam shaping using the adaptive wavefront method were described in [12]. A fiber bundle of 6000 fiber elements was used, and each element was individually controlled employing high-resolution spatial light modulators. The overall beam focus had a beam waist diameter of 1 µm, hence it can be utilized in many medical laser applications, especially for in vivo calcium imaging. Authors in [13] developed a system for the conversion of a Gaussian beam profile of a laser beam to a Bessel beam, which is a non-diverging beam, in contrast to a Gaussian beam profile. The target was achieved by placing a thin crystal cell and normal lens. To obtain an annular beam from a weak Gaussian-shaped laser beam, a liquid thermal lens effect using a Molybdenum Disulfide (MoS_2) suspension was deployed [14]. Furthermore, the study was carried out using a particle suspension in air, and almost the same results for developing an annular beam were observed. A stability of 3 h was noted in both cases. In [15] a situation in which a range of optical fibers were used as waveguides is presented. The Gaussian beam profile of the laser beam faced superposition by other present modes, hence degrading the quality of the interference pattern. This degradation is mainly due to manufacturing disorders and various strains imposed on the optical fibers. Authors in [16] used a discrete-type system to reshape a Gaussian beam profile into a uniform profile. The main optical component utilized to achieve this target is a birefringent element. J. Dworak [17] carried out laser welding using the pulse mode of the beam. However, it was demonstrated that a variety of beam shapes were essential to possibly change the welding shape and fashion through which the welding was carried out.

II. THEORETICAL BACKGROUND

An enlarged laser beam is used in diverse industrial and research applications. The nature of the laser beam constitutes a strong function of its modes of transmission from the cavity of the laser. Currently, two types of lasers are available: multimode lasers and single mode lasers. In the case of multimode lasers, the output wavelength spectrum consists of a series of peaks spreading over a range of wavelengths, which have various longitudinal modes in the beam. However, in the case of single-mode lasers, the beam contains only a single transverse mode and longitudinal mode. Therefore, a single-mode laser beam has two modes in the overall categories and only one mode in subcategories, that is, transverse and longitudinal. However, well-developed manufacturing techniques through which various modes dominate in a laser beam exist.

Laser diodes are notorious for emitting multiple modes at a time; these may be polarization, longitudinal, or transverse types. The modes were excited randomly owing to the propagation conditions envisaged by the laser beam. This is mainly due to irregularities in the interface and inside the optical fiber. During the course of beam propagation through an optical fiber, the beam encounters an inside of the fiber, such as the refractive index and manufacturing irregularities, which give rise to strain and geometric effects, which are then imposed upon the propagating beam, causing spatial separation of the modes.

Most laser applications, whether straight or interference-based, rely on the basic TEM_{00} mode because this mode can conveniently focus the beam into a high-resolution spot.

In the case of Gaussian beam profile propagation through a lens, the beam waist can be calculated using:

$$r_2 = \frac{r_o d_2}{d_1}\left(1+\frac{f_f^2}{d_1^2}\right)^{-0.5}\left\{1+\frac{d_1^4}{f_f^2}\left(1+\frac{f_f^2}{d_1^2}\right)^2\left[\frac{1}{d_2}-\frac{1}{f}+\frac{1}{d_1\left(1+\frac{f_f^2}{d_1^2}\right)}\right]^2\right\}^{\frac{1}{2}} \quad (1)$$

where r_o is the waist radius at the input side of the lens, r_2 is the waist radius at the output side of the lens, d_1 is the distance of the input waist from the lens, d_2 is the distance of the output waist from the lens, f is the focal length of the lens, and $\pi r_o^2/\lambda$ is represented by f_f.

However, with the help of other modes on the laser beam, the performance of the laser is deteriorated, which is obviously due to the shift of light energy from one spot to more than one spots, thereby affecting the performance. However, other modes are also useful depending on the type of application. For example, authors in [18] used TEM_{01} in a pulsating laser and succeeded in recording high-resolution images. The TEM_{10} mode is primarily related to the shape of the waveguide used in the laser cavity. Nonetheless, TEM_{10} mode has also been employed for particle acceleration [19]. In the TEM_{11} mode, both the transverse and longitudinal modes are present in the laser beam; therefore, the spot of the beam is seen as four quadrants of a circle. Authors in [20] developed a system for generating a subwavelength beam using the TEM_{11} mode. Such a beam is efficiently utilized in applications, such as laser drilling and data recording.

It is very likely that the original TEM_{00} mode of the laser beam is disturbed or the actual profile of the beam loses its profile, which means that the Gaussian beam profile either becomes skewed or the distribution of radiation within the beam is no more normalized. This situation may arise within systems that use optical fibers. The termination of the optical fiber requires that the end plane of the fiber be orthogonal to the axis of the optical fiber. Unless high-quality and expensive equipment is available, orthogonality is unlikely. Without proper cleaving equipment, manual cleaving of optical fiber is carried out using the score and propagation technique, and in manual scoring, keeping the angle of knife-edge perpendicular to the fiber axis remains unclear. Therefore, the cleaved edge results in a non-orthogonal face plane of the fiber. This causes the emerging beam to lose its profile.

One such situation was presented and explained in [21], where a variety of scoring instruments were used to cleave a range of optical fibers with different radii. Laser beam images were also obtained as the beams emerged from a controlled and freehand cleaving mechanism [21].

The same situation may occur during the splicing of the two optical fibers. However, the problem of minor irregularities is resolved owing to the presence of an index-matching gel inside the splice and the distance between the two fiber pieces, that is, the fiber to which the beam leaves and the fiber to which the beam is launched. Such cases have been discussed in [22], where several cases of cleavage and splicing are presented and discussed.

During the cleaving process, it is also very common for end-face defects to occur, and these defects may be in the form of cracks, contamination, and pits. The presence of pits at the end face of the fiber is inevitable because of the crystalline nature of the fiber material. These pits act as small lenses that are seen by the propagating beam; therefore, they are responsible for the major contributors to back reflections, mainly owing to the mismatch of the refractive index. These back reflections affect the beam quality in terms of power as well as the undesired transverse mode of the laser. Therefore, a remedy to these defects is commonly carried out using index matching gel at the joint.

III. METHOLOGY

During the experimentation of a fiber optic-based Laser Doppler Anemometer (LDA), the transmission fiber end encountered issues as mentioned in the previous section. Consequently, the output laser power was significantly reduced and the beam profile became scattered instead of a focused pattern. The poor beam behavior was mainly attributed to cleaving imperfections at the end face of the optical fiber.

The default solution was to apply a small amount of index matching gel at the end face of the fiber. However, because of the high viscosity (approximately 10.000 poises) and density (approximately 1 g/cm³) of the gel, along with the small cross-sectional area of the fiber, the applied layer of the index-matching gel remained uneven on the face plane of the fiber.

The uneven layer of the index matching gel raised the same concerns as that caused by cleaving imperfections. This problem typically does not occur during the splicing process because the end face of the second piece of fiber is pushed against the first fiber's face plane and locked in place. This action helps achieve an even spread of the gel. However, this problem persists in open-ended fibers and those interfacing with other discrete optical components.

To resolve this, the layer of index matching gel can be made even by attaching a tiny piece of optically flat glass to the end face of the fiber. An optically flat glass contributes minimally to any optical activity and is finely ground to within a few tens of nanometers. In this case, a microscope slide from Bolioptics with the characteristics listed in Table I was selected for this application.

TABLE I. GLASS SLIDE PARAMETERS

No.	Parameter	Description/Value
1	Glass slide application	Micro scope slide
2	Glass slide thickness	1 mm
3	Glass slide quantity per pack	50 pc
4	Glass slide dimensions	25.4 mmx76.2 mm
5	Material	Soda lime glass
6	Color	Clear
7	Net Weight	0.25 kg

A tiny piece of glass would easily stick to the end face of the optical fiber with the help of an index-matching gel. One slide was broken using a small hammer, as shown in Figure 1.

Fig. 1. View of a broken glass slide used to cover the end face of the optical fiber.

A small amount of index-matching gel was applied to the end face of the optical fiber. A small piece of broken slide, large enough to cover the full face of the fiber's cross-section, was selected for this task. The viscosity of the index-matching gel helped the tiny piece of glass to adhere to the end-face surface of the optical fiber. However, due to the small mass of the glass piece, the thickness of the index matching gel remained uneven between the fiber end and the glass piece.

To resolve this, the glass piece was delicately pressed against a flat surface to achieve an even spread of the index matching gel between the glass piece and the fiber end face. This applied pressure ensured a more uniform thickness of the gel layer, improved the optical connection, and reduced the scattering issues caused by the initial unevenness.

IV. EXPERIMENTAL RESULTS

After the preparation of the fiber, an arrangement for checking the beam profile was set up in the laboratory, as previously described [23].

The beam profile setup was based on the power ratio technique applied to a single-mode optical fiber. The end face of the fiber was loaded with index matching gel and a tiny piece of optically flat glass that was pressed against the end face. The emerging beam passed through a collimating lens. The collimated beam was then incident onto a blocking metallic wire. The cross-sectional diameter of the blocking wire was arbitrarily chosen to be 20 µm, compared to the approximated beam diameter of 4 mm. This blocking wire was mounted across a hole in a piece of the metal block. The block was also fitted with a micrometer to handle the precise movements of the block mounted with a wire.

An optical sensor head and optical meter were used to measure the beam radiation intensity. The blocking wire was moved to the approximate center of the beam. This point is achieved when the output intensity is read as the minimum. This point is normally considered to be the central point of the Gaussian distribution. From the central point of the Gaussian beam, the block was moved in 0.5 mm steps on each side of the center point. Observations on both sides of the center point were recorded, which helped determine the beam waist profiles of the incident beams, as portrayed in Figure 2.

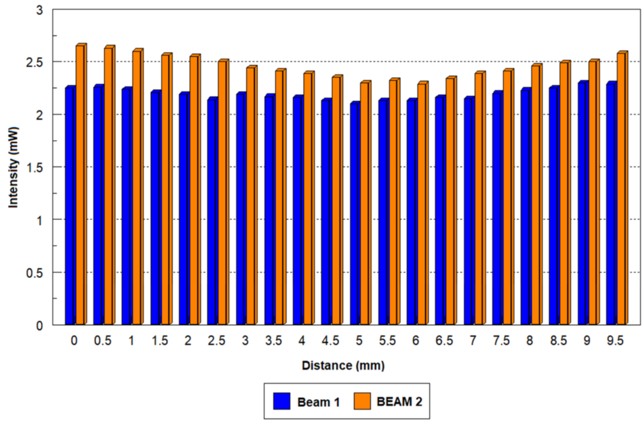

Fig. 2. Beam waist profile using the power ratio method.

In Figure 2, the intensity dip at the central points occurs because at this point the maximum intensity power is blocked by the wire, which is the apex of intensity in a Gaussian distribution. The data of Figure 2 were used to establish a normal distribution of the intensity profile. In this regard, the mean of the data was obtained using:

$$\mu = \frac{\sum x}{n} \tag{2}$$

The standard deviation of the data was calculated using:

$$\sigma = \frac{\sqrt{\sum (x_i - \mu)^2}}{N} \tag{3}$$

where σ is the standard deviation, N is the population size, x_i is the i value of the population, and μ is the population mean.

Depending on these calculations, the normal distribution is:

$$f(x) = \left(\frac{1}{\sqrt{2\pi\sigma^2}}\right)\left(e^{[-(x-\mu)^2]/2\sigma^2}\right) \tag{4}$$

The profiles of the resultant Gaussian beams as a result of the physical correction of the optical fiber end face are shown in Figures 3 and 4.

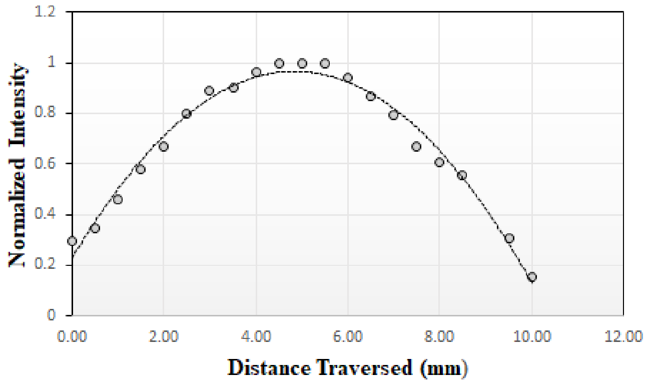

Fig. 3. Recovered Beam1 Profile.

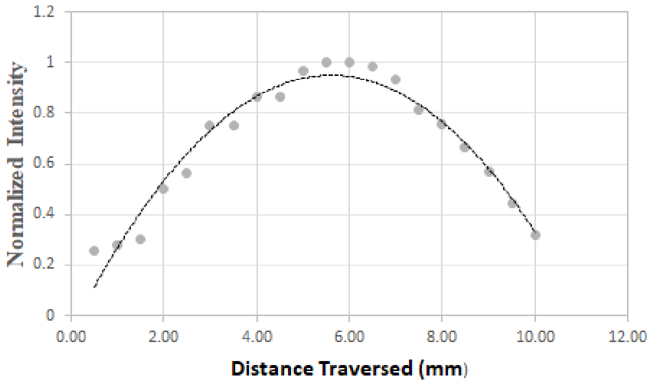

Fig. 4. Recovered Beam2 Profile.

V. CONCLUSIONS

Distortion of the laser beam profile is a major problem when a laser is used in conjunction with classical optics. However, this problem is strengthened in situations that require the use of optical fibers, especially single-mode fibers. These problems can be resolved by polishing the end face or cleaving the fiber using high-precision equipment.

In this study, a small amount of index-matching gel was applied to the end face of an optical fiber. A small piece of broken slide, which was sufficiently large to cover the full face of the fiber's cross-section, was selected for this purpose. The viscosity of the index-matching gel helped the tiny piece of glass to adhere to the end-face surface of the optical fiber. However, due to the small mass of the glass piece, the thickness of the index matching gel remained uneven between the fiber end and the glass piece. This uneven layer could lead to further optical issues, if left unresolved. To fix this, the glass piece was delicately pressed against a flat surface to achieve an even spread of the index matching gel between the glass piece and the fiber end face. This process ensured a uniform thickness of the gel, improved the optical connection, and reduced the scattering issues initially caused by uneven application.

The method suggested in this article is a promising alternative and quick setup for recovering a Gaussian beam profile. In this method, the physical correction introduced at the end face of the optical fiber has shown reliable results for the recovery of the Gaussian beam profile of the laser. The normalized profiles appear slightly negatively skewed, which may be due to measurement and setup errors. A tiny piece of optically flat glass adheres to the end face mainly because of the viscosity of the index-matching gel. This method is more reliable when working at the laboratory level. However, in a vibration environment the results may be different. This may require the application of an optical adhesive between the glass piece and cladding of the fiber itself, thereby providing a more rugged solution. The main limitation of the proposed technique is that it prevails heavily when an optical fiber is used in a closed and vibrating situation.

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