IRAQI JOURNAL OF APPLIED PHYSICS
Vol. 22, No. 2, April-June 2026, pp. 239-242

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Characterizing Laser Beam Intensity Profile Using Fiber Optics Technique

The low-cost beam-profiling approach that replaces a conventional pinhole scan with a cleaved optical fiber (quoted core ≈ 9 µm) mounted on an XY–Z translation stage is introduced in this study. The fiber tip is moved across the beam, with lateral step size of 125 µm, to obtain transverse intensity profiles for a He-Ne (632.8 nm) and a green diode laser (532 nm); measurements at multiple axial positions (z = 0.5–3 m) and geometric formulas are used to estimate the 1/e² radius w(z), far-field divergence, and the beam-quality factor M² of the laser beam. Using this technique, the smooth normal distribution appears due to the relatively small size of the fiber optic core.

Keyword: Beam profile; Pinhole technique; Optical fiber; Spot size
Received: 15 July 2025; Revised: 17 September; Accepted: 24 September 2025

1. Introduction

For assessing laser beam quality, laser beam profiling is a crucial instrument in all laser applications. It provides valuable information for the most efficient use of the laser [1-3]. In addition, it can tell how effectively optics succeeds in modifying and shaping the laser output [4]. It might only be necessary to determine the laser beam profile at the design or manufacturing stage for certain lasers and applications in order to guarantee consistent and dependable performance. In other situations, continuous laser profile monitoring is required to ensure that the laser is still functioning as intended, and to remove the junk generated during laser degradation [5, 6]. Based on all of the above, it is difficult, if not impossible, to put a laser beam into use without knowing its cross-sectional shape and how the optical power is distributed in the laser output model [7, 8]. In the majority of laser applications, lenses and other optical components are required to focus, alter, or shape the laser beam. Therefore, it is important to know the laser beam parameters such as its intensity distribution, energy measurement, waist parameter, and divergence angle [9]. A laser beam profile is a typical description of how intensity changes with distance in a plane that is perpendicular to the direction of propagation. Consequently, by determining a laser-beam-spatial-intensity profile at sites perpendicular to its path of transmission, its characteristics may be determined [10]. There are several common techniques for beam profiling, including slit-scan [11], pinhole-scan [12], and knife-edge [13]. Each of these approaches has drawbacks in specific circumstances. The slit-scan and knife-edge techniques are limitedly applied to laser beams that are radially symmetric. Although the pinhole-scan approach is superior, the setup for sensing the intensity of the collected light is more complex, and the laser spot size is frequently limited by the pinhole size to avoid being too narrow [12,14]. In this paper, we demonstrate a simple and low-cost technique that utilizes fiber optic known as the pinhole to determine the beam profile at different propagation positions, as well as the spot size, and the beam divergence.

2. Theoretical Part

When the three-dimensional wave equation is solved, the Gaussian beam often results, which describes the transversal electromagnetic modes (TEM) generated inside the laser cavity. The electric field of the lowest order transverse mode (TEM_{00}) is described by [15]:

$$E(r,z) = E_0 \frac{\omega_0}{\omega(z)} \exp\left\{-i\left[\frac{2\pi}{\lambda} z - \phi(z)\right] - r^2\left(\frac{1}{\omega^2(z)} + i\,\frac{2\pi}{\lambda}\,\frac{1}{2R(z)}\right)\right\} \quad (1)$$

Here, ω_0 is the beam waist, which is the lowest spot size achieved at ($z = 0$); $\omega(z)$ is the radius of the laser beam as a function of propagation distance z; λ is the laser wavelength; $\phi(z)$ is the Gouy phase of the optical field; r is the distance from the beam center; and R(z) is the curvature radius of the wave-front .

The corresponding intensity irradiance distribution is shown by [15]:

$$I(r,z) = I_0\ exp\left(\frac{-2r^2}{\omega^2(z)}\right) = \frac{2P}{\pi\omega_0^2}\ exp\left(\frac{-2r^2}{\omega^2(z)}\right) \quad (2)$$

Here, I_0 is a peak intensity and P is the beam total power;

The laser beam radius defined as the distance between the laser spot's center and the point where intensity decreases by factor $1/e^2$ and shown in the Fig. (1), is given by [9]:

$$\omega(z) = \omega_0 \left[1 + \left(\frac{z}{z_R}\right)^2\right]^{\frac{1}{2}} \quad (3)$$

where z_R is the Rayleigh range, given by

$$z_R = \frac{\pi\,\omega_0^2}{\lambda} \quad (4)$$

At high values of z, ω(z) is expressed as [9]:

$$\omega(z) \approx \frac{\lambda z}{\pi\omega_0} \quad (5)$$

A laser beam divergence angle is expressed as follows [9]:

$$\theta \approx \frac{\omega(z)}{z} \approx \frac{\lambda}{\pi\omega_0} \quad (6)$$

where the Eq.6 describes the laser beam diffraction-limited divergence.

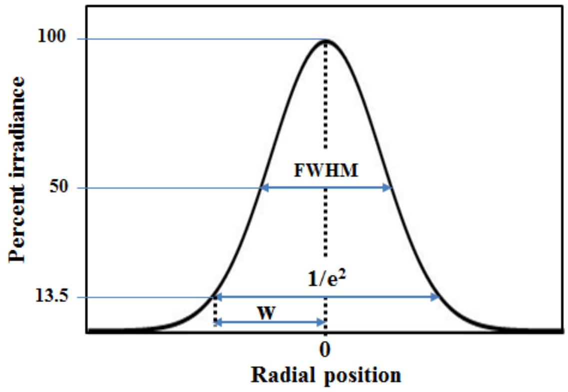

Fig. (1) Gaussian beam diagram with FWHM, 1/e², and W parameters

The beam propagation factor M^2, is a common metric used to assess a laser beam quality and used to characterize the laser beam departure from a hypothetical Gaussian. It is impossible to ignore the beam propagation factor in optical designs as it influences a laser beam properties [4,16].

When we see that (M^2=1) we get a perfect Gaussian beam while the low quality is shown if the M^2 factor value is greater than (1). However, an M^2 factor of less than (1) is impossible to get [16].

To explain the behavior of any actual laser beam, the M^2 factor generalizes the Gaussian beam propagation equations, where the beam radius is determined by [17]:

$$\omega(z) = \omega_0 \left[1 + \left(\frac{M^2\,\lambda\,z}{\pi\,\omega_0^2}\right)^2\right]^{\frac{1}{2}} \quad (7)$$

A laser beam divergence angle is expressed as follows:

$$\theta = M^2\,\frac{\lambda}{\pi\omega_0} \quad (8)$$

According to the equation above, we get

$$M^2 = \frac{\theta\,\pi\,\omega_0}{\lambda} \quad (9)$$

3. Experimental Part

Figure (2) shows a schematic diagram of the experimental setup utilized in the investigation. Two laser types were employed: a helium-neon laser emitting at 632.8 nm and a green laser diode emitting at 532 nm. The pinhole-scanning system employs silica fiber optics, with a 9 µm core diameter, a 125µm cladding diameter and a 3 mm PVC outer Jacket diameter, as a punch to measure the intensity distribution.

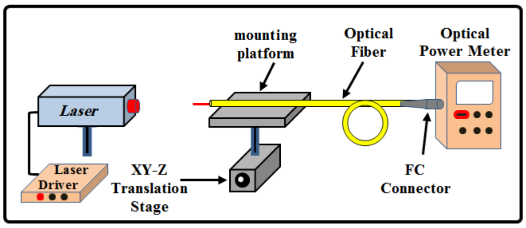

Fig. (2) Experimental setup

The exposed edge of the fiber optics, where the laser light is collected, is prepared to get the high quality end faces. Usually, this procedure entails removing the outer jacket, strengthening layer, and cladding. Then, the fiber is cleaned and cleaved to produce a perfectly flat edge which is perpendicular to the axis of the fiber as shown in Fig. (3). Afterward, the optical fiber's bare side is installed on a specialized platform that is fixed on the 3D translation stage as shown in Fig. (4). Through an (FC) connection, the optical power meter is linked to the optical fiber's opposite end. To optimize the amount of light that is recorded by the optical detector, the fiber optic head is moved in parallel and perpendicular directions to the laser spot.

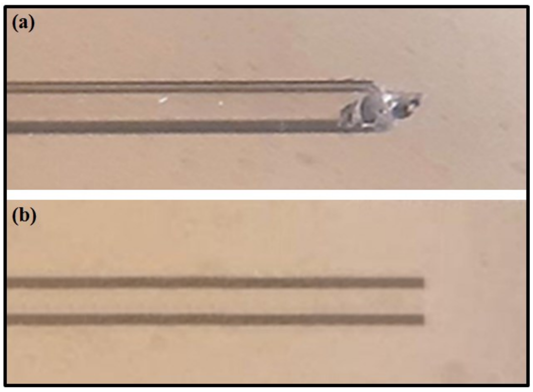

Fig. (3) The fiber optic image under a microscope: (a) Before preparing (b) After preparing

To characterize the laser beam intensity distribution, the fiber optic edge is moved crosswise across the beam at the position (z) with lateral step size of 125 µm, along the beam propagation axis. The power meter records the intensity of the laser beam traced by scanning. Subsequently, we shift the fiber tip along the beam propagation axis in increments of 0.5m. Finally, the fiber optic tip method is compared with the popular pinhole method to show the difference between them.

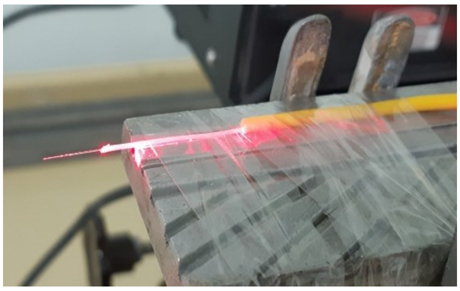

Fig. (4) Fiber optic mounted on a specialized platform

3. Results and Discussion

Figure (5) displays the intensity distribution of the He-Ne laser beam that was obtained. The scanned trace of the detected intensity of a laser beam using fiber optic tip is shown in Fig. (5a). The smooth normal distribution appears due to the relatively small size of the fiber optic core, which is about 9 µm, is less than the breadth of the beam. However, when using a common pinhole which is about 0.2 mm appears as top-hat profile as shown in Fig. (5b). This is due to the large size of the pinhole, which reduces the sensitivity of the measurement. In order to enhance the work's dependability, the previous measurements were repeated using a Green laser diode, and the same outcomes were noted, as indicated in Fig. (6).

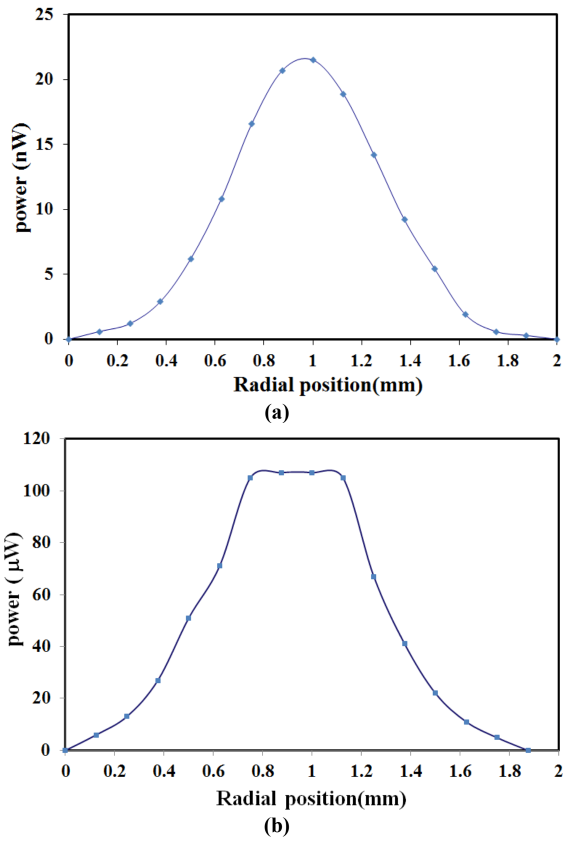

Fig. (5) The measured crosswise intensity distribution of He-Ne laser using (a) fiber optic tip (b) popular pinhole

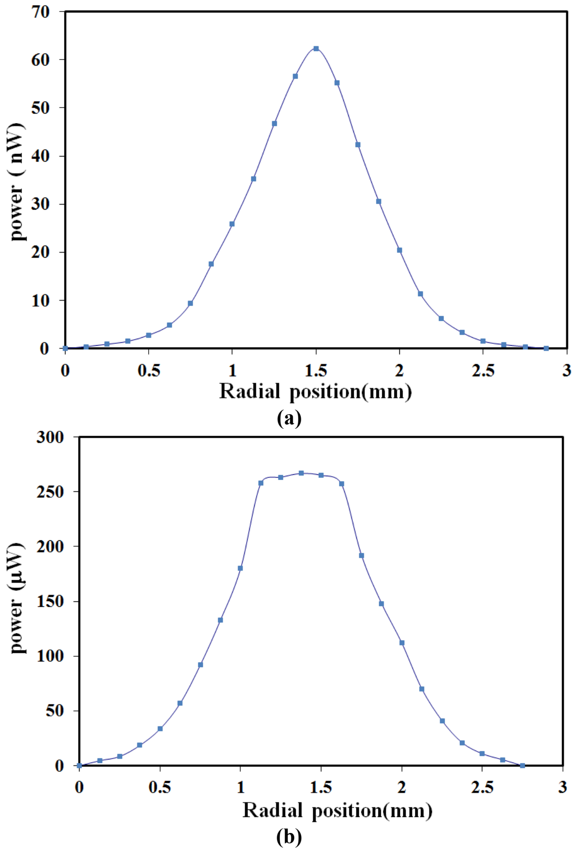

Fig. (6) The measured crosswise intensity distribution of Green laser diode using (a) fiber optic tip (b) popular pinhole

The intensity distribution of the He-Ne laser was measured by scanning the fiber optic head crosswise across the laser beam at different point along the beam propagation axis, namely 0.5, 1, 1.5, 2, 2.5, and 3 m. The laser beam radius values were found from the laser beam intensity profile curves, which denote the half-distance across the beam's center where the intensity value drop to $1/e^2$ of the maximum value, and plotted versus propagation distance of the beam as pictured in Fig. (7). The laser beam radius is shown to increase linearly with (z). This relationship is a basic property of diffraction from Fig. (7). The value of the laser beam divergence angle was found to be (0.68 mrad). By using equation (7), the beam propagation factor M2 was found to be 1.07. This aligns with the findings in [16]. Figure (8) reveals the laser beam peak power (LBPP) versus the beam propagation distance. This Figure shows that when the laser spot size increases, the laser beam peak power drops. This is due to a decrease in the number of photons per unit area when the laser spot size increases. The change equation may be expressed as follows:

$$LBPP = 15.053\, z^{-2.194} \qquad (10)$$

4. Conclusion

Using a straightforward and low-cost fiber optic technique known as "pinhole", we can easily determine the intensity profile of laser beam. One end of the fiber is mounted on a dedicated platform mounted on the 3D translation platform to collect the laser beam energy and its opposite end is connected to an optical power meter. In this technique, the fiber optic itself sends the captured light directly to the optical detector. The detector's quasi-saturation issue is successfully overcome because of the tiny core diameter of extremely inexpensive fiber optic. The measured values of the laser beam parameters show qualitative agreement with Gaussian theory. Finally, we found that this methodology has been verified as a practical and effective way to measure a Gaussian laser beam transverse intensity profile over a wide range of wavelengths. In contrast to the other techniques, it may also be utilized to determine an arbitrary laser beam intensity distribution.

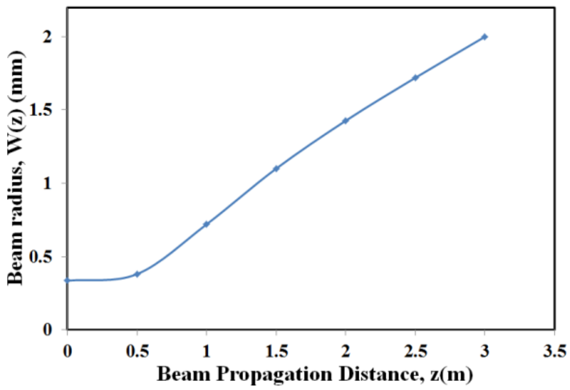

Fig. (7) Beam radius against beam propagation distance

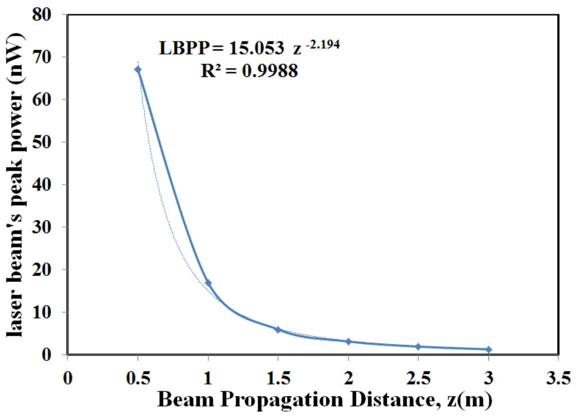

Fig. (8) Laser beam's peak power against beam propagation distance

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