APPARATUS AND DEMONSTRATION NOTES

Frank L. H. Wolfs, *Editor*

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

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Measurement of the intensity profile of a Gaussian laser beam near its focus using an optical fiber

Fang-Wen Sheu[a)]

Department of Applied Physics, National Chiayi University, Chiayi 60004, Taiwan and Graduate Institute of Optoelectronics and Solid State Electronics, National Chiayi University, Chiayi 60004, Taiwan

Ching-Huang Chang

Graduate Institute of Optoelectronics and Solid State Electronics, National Chiayi University, Chiayi 60004, Taiwan

(Received 14 June 2006; accepted 16 March 2007)

We have designed a new pinhole-scan system to measure the Gaussian intensity distribution of a He-Ne laser beam that passes through a series of lenses. Our detection device uses a single-mode optical fiber as the so-called pinhole. One side of the optical fiber is fixed on the top of a motorized translation stage to capture the laser light, and the other side is connected to an optical power meter. A digital oscilloscope is used to observe the detected light intensity. When the translation stage as well as the fiber tip is moved across the laser beam, the oscilloscope displays the scanned trace of the laser beam intensity. The evolution of the intensity distribution of a focused laser beam is measured and then fitted to distributions predicted from Gaussian optics. The measured beam waist size is compared with the result of Gaussian-beam q-parameter analysis. Using this simple system we can easily observe the transverse intensity profile of a Gaussian laser beam in the $(1+1)$-dimensional plane in the vicinity of the focus.

[DOI: 10.1119/1.2723797]

I. INTRODUCTION

Laser beam profiling is an important tool for examining the quality of a laser beam. Frequently used methods are the knife-edge method,[1,2] the pinhole-scan method,[3] and the slit-scan method.[4] The knife-edge and the slit-scan methods apply only for radially symmetric laser beams. The pinhole-scan method is a better way, but the pinhole size often limits the laser beam width not to be too small, and the setup for detecting the captured light intensity is more complicated. As illustrated in Fig. 1, the scanned trace of the detected intensity of a focused laser beam by a digital oscilloscope using a popular pinhole looks like a flat-top profile [Fig. 1(a)] because the pinhole size (about 35 μm) is bigger than the beam width, but that for using an optical fiber tip appears a smooth Gaussian distribution [Fig. 1(b)] because the fiber core size (about 8 μm) is smaller than the beam width. Therefore, in this paper we present a simple and inexpensive method, which adopts the optical fiber with a cylindrical waveguide structure as the so-called pinhole, and demonstrate it by determining the beam spot size, the beam waist size, and the q-parameters of a focused Gaussian laser beam. This technique has been confirmed to be a convenient and useful method for measuring the transverse intensity profile of a Gaussian laser beam near its focus. Yet, unlike the other methods, it is also suitable for measuring the intensity profile of an arbitrary laser beam.

II. EXPERIMENTAL SETUP AND ARRANGEMENT

A schematic diagram and photograph of the experimental system for measuring the laser beam intensity profile using an optical fiber are shown in Fig. 2. We use a He-Ne laser of 632.8-nm wavelength as the optical source. At first, the laser output beam line must be aligned to be parallel to the optical table surface using two apertures. Then we use two convex lenses, L_1 ($f_1=50$ mm) and L_2 ($f_2=150$ mm), to expand the laser beam width and collimate the laser beam precisely. Finally, we use a convex lens L_3 ($f_3=75$ mm) to focus the laser beam, which is then prepared for the intensity profile measurement. It is important to notice that, in fact, the laser

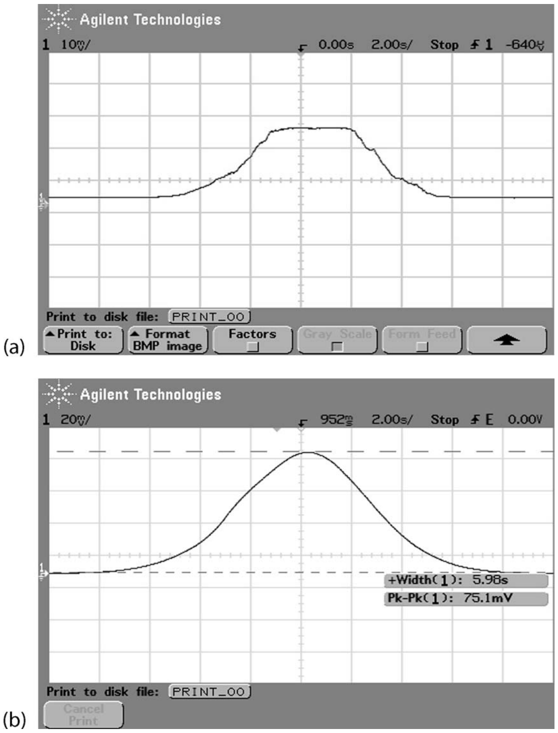

Fig. 1. The representative digital oscilloscope traces of the detected intensity of a focused laser beam using (a) a pinhole and (b) an optical fiber tip. The horizontal (temporal scan) unit is 2.0 s per division. The vertical (detector voltage) unit is (a) 10 mV per division and (b) 20 mV per division, respectively. The scan speed of the automatic translation stage is 0.0125 mm/s.

output beam is initially a bit divergent. Therefore, it is necessary to produce a well-collimated laser beam; otherwise the measurement results will not be consistent when the focusing lens L_3 is inserted at different locations. Furthermore, the laser beam is arranged to be three times wider before being focused so that the focused beam has a sufficiently sharp variation of its intensity distribution within a short distance of propagation.

We have designed an improved pinhole-scan system to measure the Gaussian intensity distribution of the focused laser beam after it has passed through the focusing lens L_3. Our detection device uses a pigtailed single-mode optical fiber (Corning SMF-28 with core diameter about 8 μm) as the so-called pinhole. The bare side of the optical fiber used to capture the laser light is cleaved vertically and fixed on the top of a motorized translation stage, and the other side of the optical fiber is connected to an optical power meter through a FC/PC (physical contact, end face polished convex) connector and an adapter, as shown in Figs. 3(a) and 3(b), respectively. A digital oscilloscope is used to record the signal from the optical power meter. When the translation stage as well as the fiber tip is moved across the laser beam, the oscilloscope displays the scanned trace of the laser beam intensity, as shown in Fig. 1(b).

III. EXPERIMENTAL RESULTS AND ANALYSIS

Initially, we control the translation stage manually along the directions parallel to and orthogonal to the laser beam to

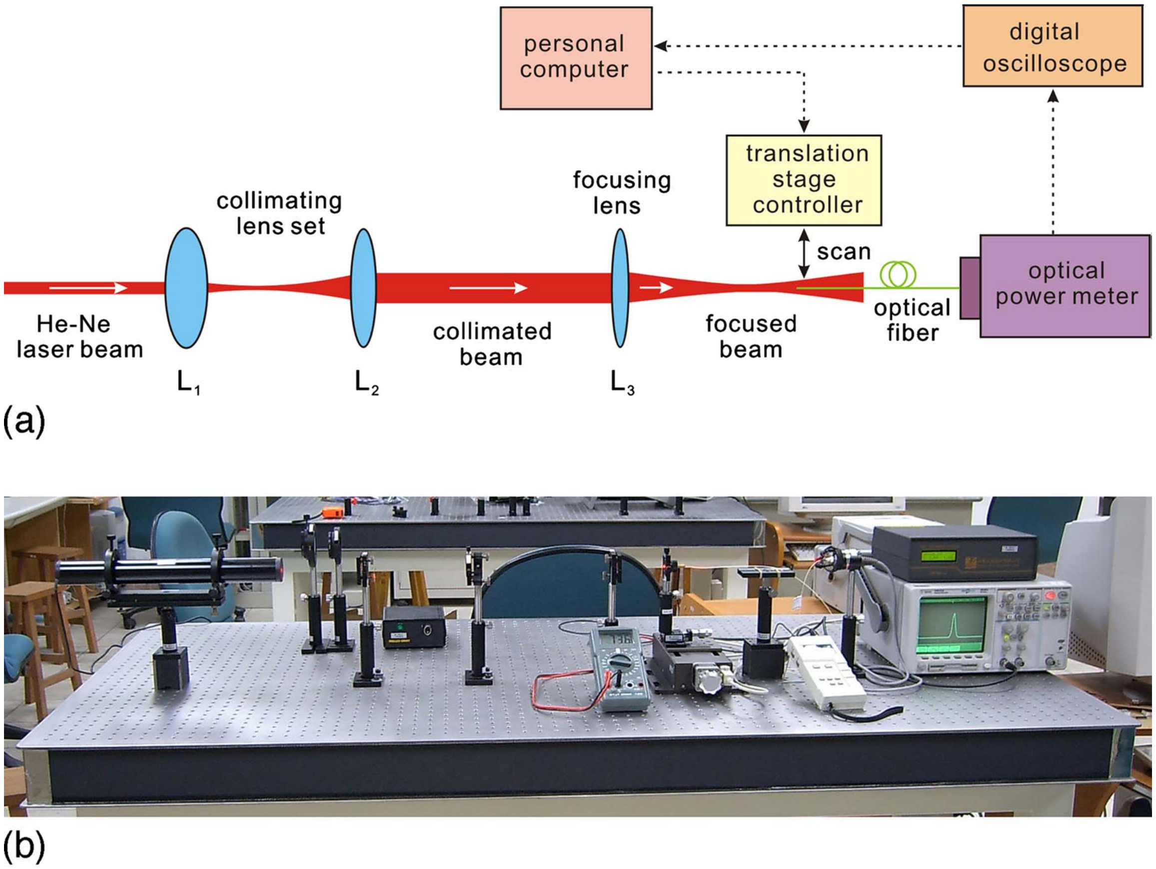

Fig. 2. (a) A schematic diagram and (b) photograph of the experimental system.

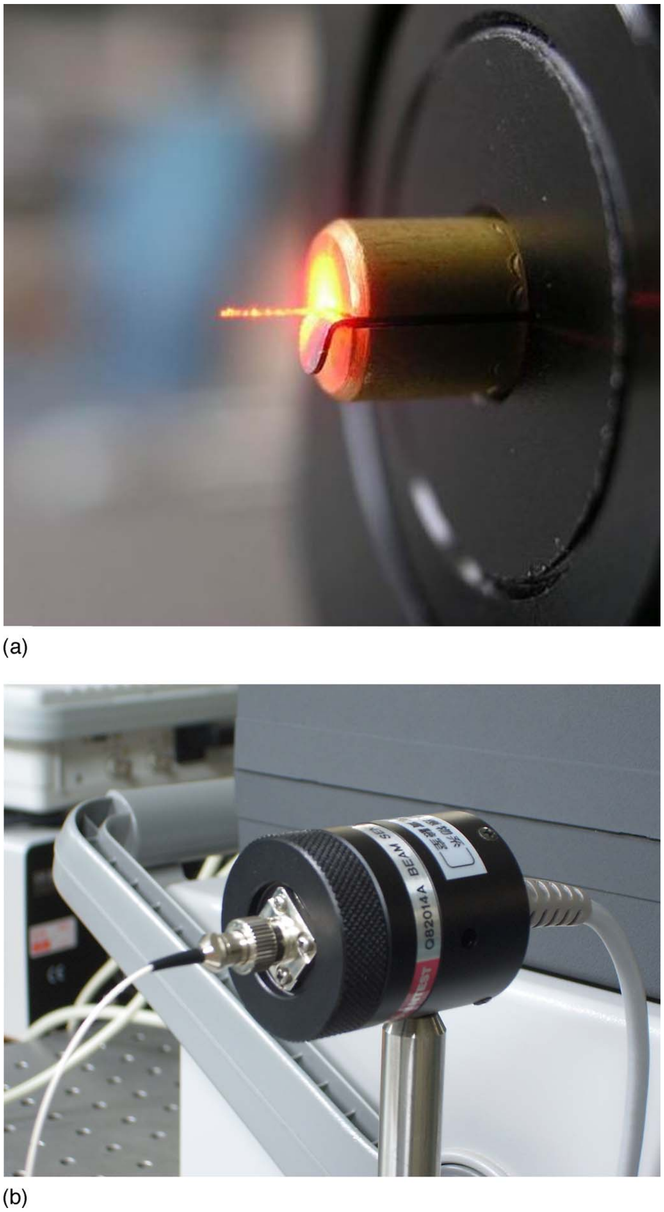

Fig. 3. (a) The bare side of the pigtailed single-mode optical fiber is mounted in a fiber chuck. (b) The other side of the optical fiber is connected to an optical power meter through a FC/PC connector and an adapter.

maximize the light intensity captured by the fiber tip of the detector system. As a result, we can set the starting location of measurement at the focal point of the laser beam. In the next step, we move the fiber tip successively in increments of 1 mm to the front and to the rear of the focal point (about ±10 mm range) along the beam propagation axis. At every longitudinal situation, the fiber tip is scanned transversely across the laser beam by the automatic translation stage at a step size of 0.00125 mm in order to measure the intensity profile of the laser beam at that longitudinal sampling position. The measured transverse intensity profiles of a focused laser beam in a three-dimensional style, and the calculated beam spot sizes, are plotted as a function of the beam propagation distance in Fig. 4. The Gaussian beam sizes are calculated by fitting the intensity profiles with Gaussian distributions. The size of the beam waist w_{02} at the focal point is found to be 0.0125 mm.

The measured beam waist size is then compared with the result of Gaussian-beam q-parameter analysis,[5,6] as outlined below. We start by writing out the ABCD ray matrix that applies from the input plane 1, just before the focusing lens L_3 of focal length f_3, to the focal plane 2, a distance d away from the lens L_3:

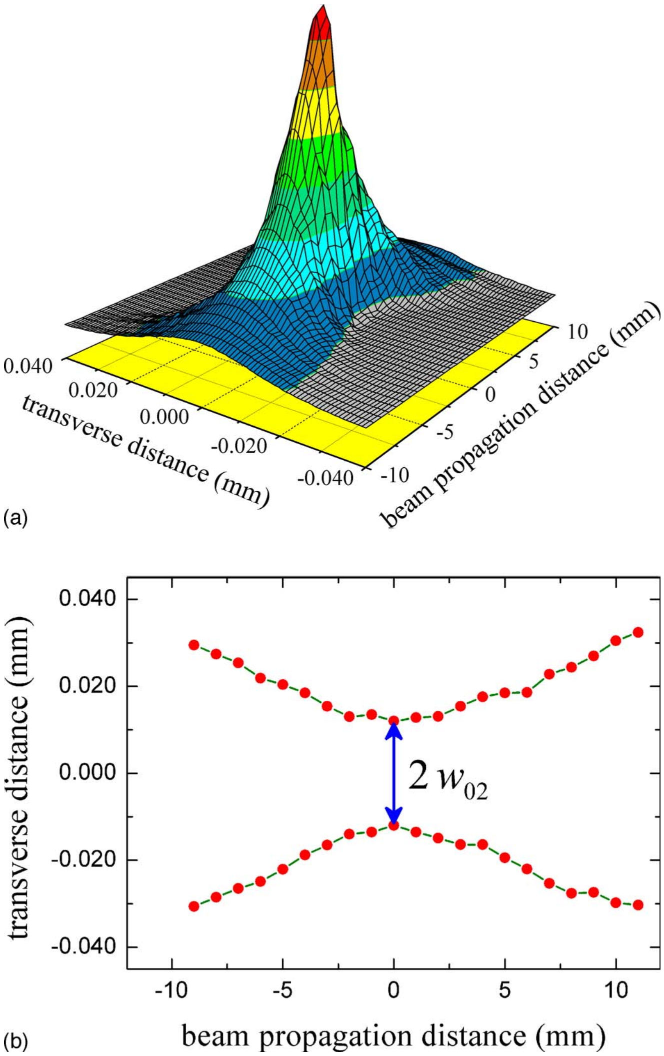

Fig. 4. (a) The measured transverse intensity profiles of a focused laser beam in a three-dimensional style, and (b) the calculated beam spot sizes, are plotted as a function of the beam propagation distance.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f_3} & 1 \end{bmatrix} = \begin{bmatrix} 1-\dfrac{d}{f_3} & d \\ -\dfrac{1}{f_3} & 1 \end{bmatrix}, \tag{1}$$

where A, B, C, D are the elements of the ray matrix that relates the ray at plane 2 to the ray at plane 1. The q parameter of a Gaussian laser beam, or the complex beam radius, can be expressed as

$$\frac{1}{q} = \frac{1}{R} - i\frac{\lambda}{n\pi w^2}, \tag{2}$$

where R is the radius of curvature of the beam wave front, w is the beam spot size, λ is the optical wavelength, and n is the refractive index (we take $n=1$ in air). The physical significance of q can be revealed by inserting the expression of Eq. (2) into the part of the field complex amplitude that involves r

$$\psi \propto \exp\left[-i\frac{kr^2}{2q}\right] = \exp\left[-i\frac{kr^2}{2R}\right]\exp\left[-\frac{r^2}{w^2}\right], \tag{3}$$

where $k = 2\pi n/\lambda$ is the beam propagation constant. We then take the collimated incident beam parameter as q_1 and the focused output beam at the focal point as q_2. Since the radius of curvature R_1 of a collimated laser beam is infinite, we obtain

$$q_1 = i\frac{n\pi w_{01}^2}{\lambda}, \tag{4}$$

where w_{01} is the spot size of the collimated incident beam. Using the transformation law in Gaussian optics, we obtain

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D} = \frac{(1 - d/f_3)i(n\pi w_{01}^2)/\lambda + d}{(-1/f_3)i(n\pi w_{01}^2)/\lambda + 1}, \tag{5}$$

which may be simplified to give

$$q_2 = \frac{[d - (1/f_3)(n\pi w_{01}^2/\lambda)^2 + d(1/f_3)^2(n\pi w_{01}^2/\lambda)^2] + i(n\pi w_{01}^2)/\lambda}{1 + (1/f_3)^2(n\pi w_{01}^2/\lambda)^2}. \tag{6}$$

Since the radius of curvature R_2 at the focal point is also infinite, the real part of q_2 must be zero. So we have

$$d - \frac{1}{f_3}\left(\frac{n\pi w_{01}^2}{\lambda}\right)^2 + d\left(\frac{1}{f_3}\right)^2\left(\frac{n\pi w_{01}^2}{\lambda}\right)^2 = 0, \tag{7}$$

and, hence,

$$d = \frac{f_3}{1 + [f_3/(n\pi w_{01}^2/\lambda)]^2}. \tag{8}$$

Equation (6) then gives the resultant parameter q_2 at the focal point

$$q_2 = i\frac{n\pi w_{02}^2}{\lambda} = \frac{i\dfrac{n\pi w_{01}^2}{\lambda}}{1 + (1/f_3)^2(n\pi w_{01}^2/\lambda)^2}. \tag{9}$$

The square of the beam waist size after the focusing lens L_3 is therefore equal to

$$w_{02}^2 = \frac{w_{01}^2}{1 + (1/f_3)^2(n\pi w_{01}^2/\lambda)^2}. \tag{10}$$

We have measured independently the incident beam spot size, w_{01}, of the collimated laser beam to be 1.27 mm using the same method as above. Substituting the values of w_{01} and f_3 into the expression for the beam waist size w_{02} of Eq. (10), derived from the q-parameter analysis above, we obtain the theoretical value of the beam waist size w_{02} to be 0.0119 mm, which is very close to the experimental value 0.0125 mm, which is an error of only about 5%. This shows that using a pigtailed single-mode optical fiber to scan a laser beam is a practical way to measure the intensity profile of a focused laser beam.

IV. CONCLUSION

Using a pigtailed single-mode optical fiber as the so-called pinhole, we can easily measure the transverse intensity profile of a Gaussian laser beam in the $(1+1)$-dimensional plane in the vicinity of a focus by the pinhole-scan method. This teaching experiment is suitable for an undergraduate optics laboratory course. Due to the small core size of very cheap optical fiber, the quasi-saturation problem of the detector is avoided effectively. The captured light could also be transmitted directly to the optical power meter by the optical fiber itself. The measured beam waist size is compared with the result of Gaussian-beam q-parameter analysis, and shows good agreement.

ACKNOWLEDGMENTS

We acknowledge financial support from the National Science Council, Taiwan, through project NSC-93-2112-M-415-004.

[a] Corresponding author. Telephone: 886-5-2717993; Fax: 886-5-2717909. Electronic mail: fwsheu@mail.ncyu.edu.tw

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