

## Determination of Beam Width and Quality for Pulsed Lasers Using the Knife-Edge Method

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### ABSTRACT

In this work, we present a simple theoretical formalism for beam measurements using the knife-edge technique, applied to non-Gaussian laser beams, as well as its application to the characterization of a pulsed laser beam. The beam waist and the  $M^2$  parameter of a laser beam from a home-made, pulsed, Er: Tm: Ho: YLF laser were determined using this simple and inexpensive method. The obtained values of the  $M^2$  were 6.8 and 9.0, respectively, to  $x$  and  $y$  directions.

*Key Words:* YLF; Laser; Knife edge; Beam quality.

### INTRODUCTION

Accurate characterization of laser beams has become an important procedure for many laser applications. The well-known knife-edge technique<sup>[1,2]</sup> allows the determination of

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Gaussian beam profiles in a simple and inexpensive way. In this paper, we review the theory of this simple method and present some experimental results. The measurement could be realized by using only a detector and a blade coupled to a micrometer. The beam profile characterization will be very helpful when coupling the beam to an optical fiber, in order to facilitate its use in the biomedical area.<sup>[3,4]</sup>

### THEORETICAL REVIEW

For symmetric Gaussian beams, the intensity  $I(x, y)$  is usually given by:

$$I(x, y) = I_0 \exp \left[ -2 \frac{(x - x_0)^2 + (y - y_0)^2}{w^2} \right] \quad (1)$$

where  $w$  is the beam radius. The total power is obtained by the integration of  $I(x, y)$ , as indicated in Eq. (2).

$$P_T = \int_{-\infty}^{+\infty} dx \int_{-\infty}^{+\infty} dy I(x, y) = \frac{\pi w^2 I_0}{2} \quad (2)$$

The drawing in Fig. 1 represents the transversal profile of a Gaussian beam eclipsed by the knife-edge. The transmitted power is expressed by Eq. (3):

$$P(x, y) = \int_x^{+\infty} dx' \int_y^{+\infty} dy' I(x', y') \quad (3)$$

By measuring the transmitted power with the shift of one knife in the  $x$  or  $y$  direction, it is possible, by using Eq. (3), to determine the beam radius,  $w_x$  or  $w_y$ , and position.

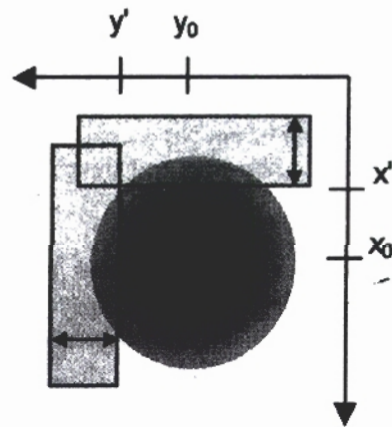


Figure 1. Transversal profile of a Gaussian beam during knife-edge measurement.

However, Eq. (3) has no known analytical solution. Khosrofiyan et al.<sup>[5]</sup> have proposed a simpler, equivalent mathematical expression to Eq. (3):

$$P_N(x) = \frac{1}{1 + \exp[-(a_0 + a_1 t + a_2 t^2 + a_3 t^3)]} \quad (4)$$

where  $a_0 = -6.71387 \times 10^{-3}$ ,  $a_1 = -1.55115$ ,  $a_2 = -5.13306 \times 10^{-2}$ ,  $a_3 = -5.49164 \times 10^{-2}$ ,  $t = (2/w_x)(x - x_0)$  and  $P_N(x) = P(x)/P_T$  is the normalized power. A similar expression to  $P_N(y)$  can be written using this approach. The error in the determination of the  $w$ , using this alternative expression, is only 0.05%. This is of the same order of the experimental errors at best condition. By using this expression, the parameters  $w_x$  and  $x_0$  in Eq. (4) can be easily fitted to the experimental data. For a fundamental Gaussian beam, its propagation is completely characterized by the beam waist,  $w_0$ , and waist position,  $z_0$ . The beam radius as a function of  $z$ ,  $w(z)$ , can be calculated using the following expression:

$$w(z) = w_0 \sqrt{1 + \left[ \frac{\lambda(z - z_0)}{\pi w_0^2} \right]^2} \quad (5)$$

where  $\lambda$  is the laser wavelength.

However, considering a non-Gaussian laser beam, there is a simple model [similar to Eq. (5)] to represent it including a dimensionless propagation factor  $M^2$ :<sup>[6]</sup>

$$M^2 = \frac{\pi w_0^2}{2\lambda(z - z_0)} \left( \frac{w^2}{w_0^2} - 1 \right)^{1/2} \quad (6)$$

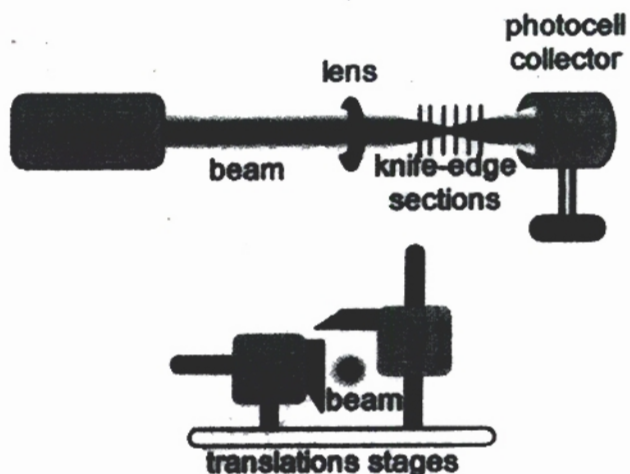
## EXPERIMENTAL

We used a standard razor blade coupled to a translation stage with precision of 5  $\mu\text{m}$ . The beam under study is from a Er: Tm: Ho: YLF laser prototype, emitting at 2.06  $\mu\text{m}$ , developed at CLA (Centro de Lasers e Aplicações) from IPEN/CNEN-SP.<sup>[7]</sup> The laser beam was focused by a 100 mm-quartz lens and the transmitted beam energy was measured by using a piro-electric detector FieldMaster-Coherent. The measurements of the  $z$  values had error of 0.5 mm.

## RESULTS AND DISCUSSION

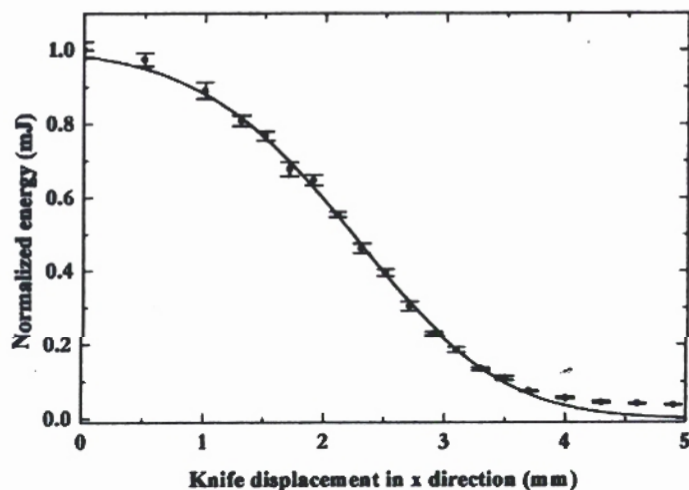
A typical set of measurements of the normalized transmitted power, in a run of the knife-edge position, is shown in Fig. 3 for the  $x$  direction case. By fitting expression 4 to the data, it is possible to determine the parameters  $w_x$  and  $x_0$ , as depicted in the figure.

By performing some determinations of  $x_0$ ,  $y_0$ ,  $w_x$ , and  $w_y$  along the  $z$  direction, it is possible to assemble a table of parameters that describes the beam propagation. Usually, it is more relevant to have an analytical expression to describe it, in order to calculate beam transformations. The  $x_0(z)$  and  $y_0(z)$  data have no relevant information, since the eventual



**Figure 2.** Experimental setup for the beam analyzer devices and the translation stage coupled with the knife-edge.

beam misalignment can be experimentally corrected to a situation where  $x_0(z) = y_0(z) = \text{constant}$ . On the contrary, the  $w_{x,y}$  data have valuable information about the beam behavior. The fit of expression 6 to the  $w_{x,y}(z)$  data can supply the values of the beam waists, waist positions, and quality factors:  $w_{0x}$ ,  $w_{0y}$ ,  $z_{0x}$ ,  $z_{0y}$ ,  $M_x^2$ ,  $M_y^2$ . Thus, by this method, beam astigmatism can be also easily determined. The individual values of  $w_x$  and  $w_y$ , as well as the obtained final beam parameters for the pulsed laser beam under characterization are shown in Figs. 4 and 5, respectively.



**Figure 3.** Measured normalized transmitted power as a function of the knife-edge position in the  $x$  direction. Also shows expression 4 fitted to the data.

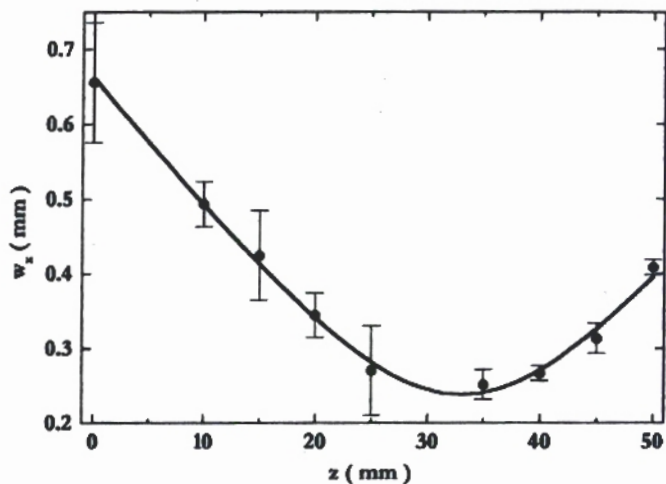


Figure 4. Set of  $w_x$  data obtained by the knife-edge measurements and expression 6 with fitted parameters.

CONCLUSION

By using the simple method described, it was possible to completely characterize the beam from our home-made pulsed laser, the Er : Tm : Ho : YLF prototype. No astigmatism was detected, since there is no significant differences between  $w_{0x}$  and  $w_{0y}$ , as well as

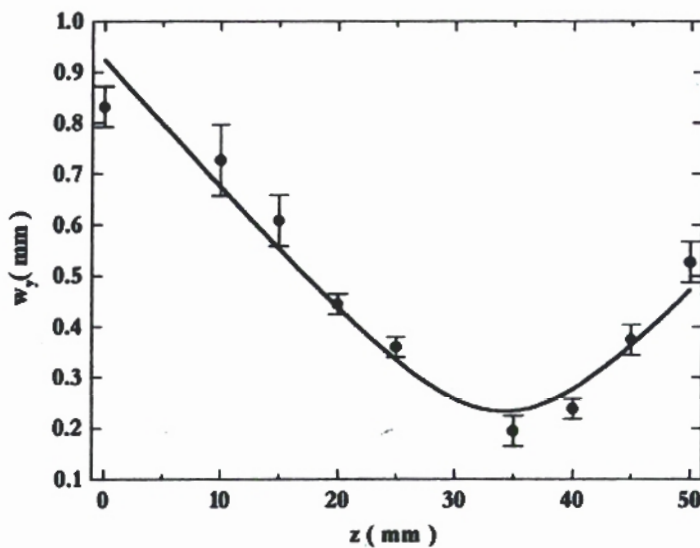


Figure 5. Set of  $w_y$  data obtained by the knife-edge measurements and expression 6 with fitted parameters.

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between  $z_{0x}$  and  $z_{0y}$ . However, the  $M^2$  values presented a difference that can be explained by a slight difference in the aberrations thermally produced inside the laser rod. The  $M^2$  values were around 8, which corresponds to a good beam quality for a pulsed laser beam. This characterization will be very helpful when coupling the beam to an optical fiber, in order to facilitate its use in the biomedical area.

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Received May 19, 2002

Accepted June 22, 2002

Manuscript 1341