Gaussian laser beam diameter measurement using a quadrant photodiode

T. W. Ng
Faculty of Engineering, Engineering Block EA-07-32, National University of Singapore, 9 Engineering Drive 1, Singapore 117576

S. L. Foo
Seagate Technology International, 7000 Ang Mo Kio Ave 5, Singapore 569877

H. Y. Tan
Faculty of Engineering, Engineering Block EA-07-32, National University of Singapore, 9 Engineering Drive 1, Singapore 117576

(Received 30 January 2005; accepted 17 April 2005; published online 1 June 2005)

Gaussian laser beam diameters are typically measured using knife-edges or gratings. Both require precise alignment with the photodiode placed after them from the laser source. In addition, beam diameter measurement in two orthogonal axes is only possible via rotation of the knife-edge or grating. Here, we report a novel measurement method that uses a relatively inexpensive and robust quadrant photodiode to circumvent the alignment requirement as well as allow two axes laser beam diameter measurement without rotation of any component. The theoretical basis of this approach is described and experimental results using it are presented. This method portends possibilities in the design of instrumentation that integrates Gaussian laser beam diameter measurement with laser beam tracking in a compact manner using fewer components.
[DOI: 10.1063/1.1928189]

Accurate knowledge of the Gaussian laser beam diameter is useful in many areas. These include optical data recording,[1] laser lithography,[2] photodiode nonlinearity characterization,[3] and photothermal diffusivity measurements.[4] Some of the practical methods used to measure the Gaussian laser diameter include the usage of burn spots,[5] knife-edges,[6,7] and gratings.[8,9] The burn spot method is generally inaccurate and suited for interrogating the output from high power lasers. While the knife-edge and grating methods both possess high accuracies, precise alignment between the knife-edge/grating with the photodiode, often placed after it from the laser light source, is important as a less than careful set up will result in erroneous measurements. Furthermore, it may be necessary to measure the beam diameter in two orthogonal axes in certain applications or simply to ascertain that the laser illumination is normal to the detector plane (a non-normal illumination will result in an elliptic as opposed to a circular Gaussian beam profile). With the knife-edge or grating methods, it would be necessary to rotate these entities orthogonally in-between each measurement. This requires the addition of a precise optomechanical stage to the setup.

The quadrant photodiode is a proven sensor used for laser beam position tracking. It is relatively low-cost and robust in nature. Its use had been reported in areas such as atomic force microscopy,[10] particle tracking,[11] and photothermal diffusivity measurements.[12] Here, we describe the use of the quadrant photodiode as an inexpensive device to measure the Gaussian laser beam diameter.

In the proposed approach, the Gaussian laser beam illuminates the quadrant photodiode directly [see Fig. 1(a)]. As light impinges on each quadrant, voltages proportional to the amount of light power incident are generated [Fig. 1(b)]. Let the voltages generated from each quadrant be V_1, V_2, V_3, and V_4, respectively. If the readings are to be obtained in a bicell fashion to interrogate the left, right, top, and bottom values, they can be derived respectively using

$$V_L = V_1 + V_4,\ V_R = V_2 + V_3,\ V_T = V_1 + V_2,\ V_B = V_3 + V_4. \tag{1}$$

Clearly, V_L or V_R can be used to find the beam diameter along the x-axis while using V_T or V_B allows measurement of the beam diameter along the y-axis. Suppose that the total power of the laser beam is P_o. As the quadrant photodiode is moved in the x-axis, the power corresponding to V_L or V_R at any position X can be determined using

$$P(X) = \left(\frac{2}{\pi}\right)^{1/2} \frac{P_o}{w} \int_X^\infty \exp(-2x^2/w^2)dx \tag{2}$$

where w is the beam radius at the $\exp(-2)$ points in intensity. By creating the following variable:

$$\beta = \frac{\sqrt{2}}{w}x \tag{3}$$

the expression in Eq. (2) reduces to

$$\frac{P(X)}{P_o} = \frac{1}{2}\,\mathrm{erfc}(\beta). \tag{4a}$$

Values of $P(X)/P_o$ between 0.1 and 0.9 correspond to β having values of 0.9062 and −0.9062, respectively. Therefore the beam radius is given by

$$w = 0.7803(X_2 - X_1), \tag{4b}$$

where $(X_2 - X_1)$ is the translation between the 0.9 and 0.1 points. A similar approach of moving the quadrant photodi-

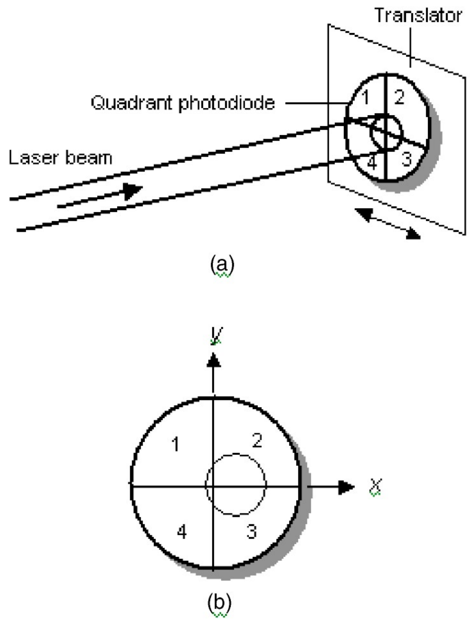

FIG. 1. Schematic description of the Gaussian laser beam diameter measurement method using a quadrant photodiode.

ode in the y-axis, and interrogating either V_L or V_R will give the beam radius in that axis.

A commercially available quadrant photodiode (Pacific Silicon QP50-6SD) was used for the verification. The laser used was a He–Ne model with 10 mW power and 632.8 nm wavelength. The quadrant photodiode was mounted on an x–y optical translation stage with 10 microns resolution along each axis of travel.

In the determination of laser beam diameter along the x-axis, the quadrant photodiode was first positioned such that the laser beam illuminated the top and bottom quadrants almost equally. Subsequently, readings with the quadrants were made as the photodiode was translated in the x-axis. From the voltage readings, the values of V_L and V_R were calculated. A similar procedure in the y-axis was applied to determine the diameter along this axis. From the quadrant voltage readings, the values of V_T and V_B were calculated.

Figure 2 gives the plots of V_L and V_R against translation of the quadrant photodiode in the x-direction. It can be seen that they are exact mirror images of each other. By identifying $P(X)/P_o$ equal to 0.1 and 0.9 in each plot, the beam diameters were calculated using Eq. (4) and found to be 1.10 mm for each plot. The similar values confirm the working principle.

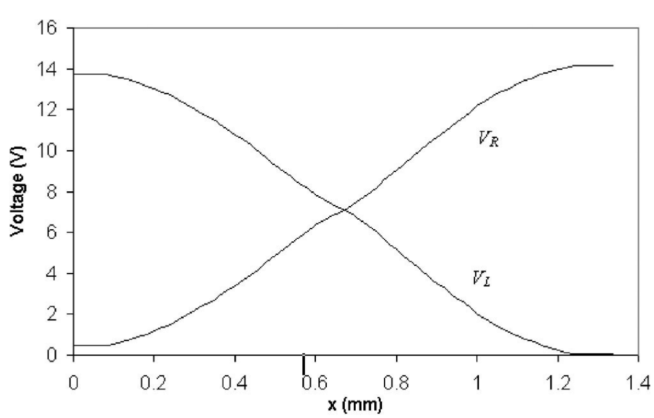

FIG. 2. Plots of V_L and V_R against translation of the quadrant photodiode in the x-direction.

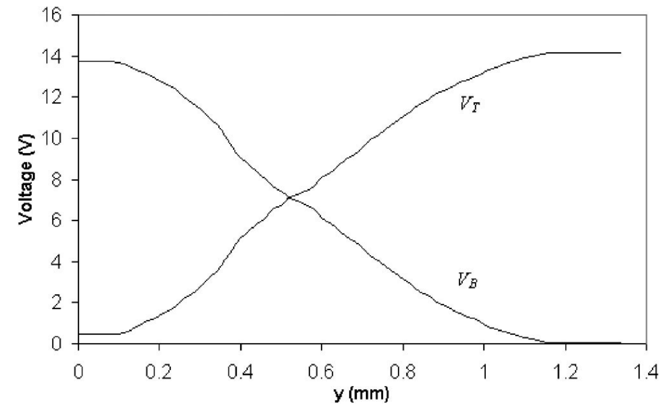

FIG. 3. Plots of V_T and V_B against translation of the quadrant photodiode in the y-direction.

Figure 3 gives the plots of V_T and V_B against translation of the quadrant photodiode in the y-direction. The trends obtained were similar to the case in Fig. 2. The beam diameters were found to be 1.09 mm for each plot. Again, the similar values confirm the working principle. That the beam diameters in both the x and y axis were different by only 1% from each each other indicates the circular nature of the Gaussian laser beam used in the experiment.

The quadrant photodiode clearly provides an easy way of determining the Gaussian laser beam diameter. The accuracy of this technique is limited only by the resolution of the translator used to move the quadrant photodiode. By removing the need for any intervening elements (such as knife-edge and grating) a more robust measuring system is afforded. The effects of imperfections in the knife-edge and grating on measurement accuracy are well known.

An added advantage with the approach reported here lies in the possibility of integrating a laser beam diameter measurement feature into instruments that use the quadrant photodiode to track beam deflection. The approach here permits designs that are compact and that use fewer components.

It should be noted that while the technique described here allows measurement of laser beam diameters that are dissimilar in two axes, there is a need to first orient the

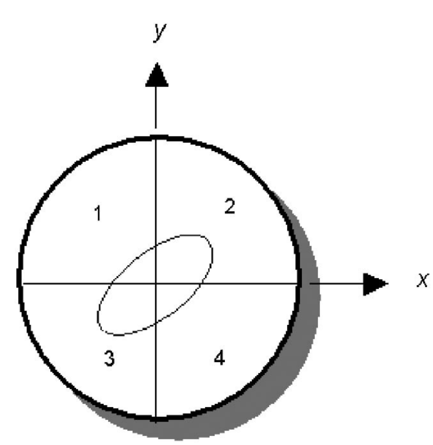

FIG. 4. A Gaussian elliptical laser beam that has the principal axis not coincident with the x or y axis of the quadrant photodiode.

principal elliptical axes of the beam to coincide with the x or y axis of the quadrant photodiode. Such a situation is illustrated in Fig. 4. This can be easily achieved by first ensuring that the centers of the laser beam and quadrant photodiode are coincident using $V_L = V_R$ and $V_T = V_B$. By next interrogating the values V_1, V_2, V_3, and V_4, the extent of rotational misalignment of the elliptical principal axis from the x or y axis can be ascertained. This should then permit the necessary corrections to be introduced to either the laser source or quadrant photodiode.

In summary, a novel Gaussian laser beam diameter measurement method that uses a relatively inexpensive and robust quadrant photodiode is reported. It circumvents the alignment requirement needed with knife-edges and gratings and allows two axes laser beam diameter measurement without the rotation of any component. The approach is demonstatrated to provide accurate measurements in a verification experiment. This technique opens up exciting vistas in the design of instrumentation that integrates Gaussian laser beam diameter measurement with laser beam tracking in a compact manner using fewer components.

[1] J. Seto, S. Tamura, N. Asai, N. Kishii, Y. Kijima, and N. Matsuzawa, Pure Appl. Chem. **68**, 1429 (1996).
[2] C. G. Chen, P. T. Konkola, R. K. Heilmann, G. S. Pati, and M. L. Schattenburg, J. Vac. Sci. Technol. B **19**, 2335 (2001).
[3] T. Kubarsepp, A. Haapalinna, P. Karha, and E. Ikonen, Appl. Opt. **37**, 2716 (1998).
[4] C. Martinsons, A. Levick, and G. Edwards, Anal. Sci. **17**, s114 (2001).
[5] Y. C. Kiang and R. W. Lang, Appl. Opt. **22**, 1296 (1983).
[6] J. A. Arnaud, W. M. Hubbard, G. D. Mandeville, B. de la Claviere, E. A. Franke, and J. M. Franke, Appl. Opt. **10**, 2775 (1971).
[7] D. K. Cohen, B. Little, F. S. Luecke, E. A. Franke, and J. M. Franke, Appl. Opt. **23**, 637 (1984).
[8] M. A. Karim, A. A. S. Awwal, A. M. Nasiruddin, A. Basit, D. S. Vedak, C. C. Smith, and G. D. Miller, Opt. Lett. **12**, 93 (1987).
[9] A. K. Cheri and M. S. Alam, Opt. Commun. **223**, 255 (2003).
[10] K. Nakano, Rev. Sci. Instrum. **71**, 137 (2000).
[11] A. Rohrbach and E. H. K. Stelzer, J. Appl. Phys. **91**, 5474 (2002).
[12] A. Salazar, A. Sanchez-Lavega, and J. Fernandez, J. Appl. Phys. **65**, 4150 (1989).