Development of a novel beam profiling prototype with laser self-mixing via the knife-edge approach

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ABSTRACT

Laser is widely used in industry, biomedical and other kinds of fields. Beam size is the most important parameter among the laser variables. Typical state-of-the-art profiling techniques employ either a scanning-based or camera-based system, using photodiodes or image sensors as the signal receiver. Despite their profiling capabilities, these systems do not tend to be budget-friendly and easy to operate. In this paper, a novel cost-effective beam profiling prototype based on self-mixing interference was developed to measure the Full Width Half Maximum (FWHM) of a range of laser diodes by the knife-edge approach. The difference between our prototype and other systems is that the photodiode is placed behind the laser source, and beam size is calculated by analyzing the feedback signal. A commercial camera beam profiler was used to benchmark our prototype. Results show that though there is a variation of 45.29% between the measured beam size and the integrated beam size in the x directions due to diffuse and specular reflection, our USD 200 prototype has a high accuracy on the prediction of laser beam sizes. Our prototype could provide accurate predicted beam size for Gaussian-alike beam. This is the very first study to explore the application of self-mixing interference in laser beam profiling. It is believed that our proposed approach has contributed to the on-going development of laser beam profiling methodology.

Keywords: Laser diode package; Gaussian beam; Laser self-mixing interference; Beam size measurement; Knife-edge measurement

1. INTRODUCTION

Laser has been applied in the fields of laser material processing, laser medicine, laser spectroscopy, and laser detection [1-5]. The optimization of laser parameters has never stopped, and it is very necessary to accurately determine the resolution (size) of the laser beam [6]. The laser beam size is an important parameter that marks the performance of the laser, and users are very concerned about it in practical applications, such as laser cutting, laser drilling, and remote welding in industry. In addition, other parameters of the laser, like beam optical intensity, are calculated based on the beam size [7]. Beam profiler is used to capture the distribution of laser optical intensity to obtain the beam size. Beam profiler can be divided into two types, one is camera-based system, the other is scanning based system [8-10]. Compared with the scanning-based system, the camera-based system has many advantages, such as it can detect and display any structure that may exist on the sensor. Camera beam profiler can also provide three dimensions of the laser beam, while the scanning-based system can only measure one or two dimensions at a time. The aim of this study is to provide an accurate, easy-operation, cost-affordable system to measure the laser beam size by a simple experiment set up [11].

At present, lots of researchers have successfully achieved the identification of the laser beam size by means of scanning knife-edge, scanning aperture, and burning patterns. Katherine Purvis et al. [12] developed a CMOS-based camera, which was placed behind the knife-edge to measure the laser beam size. Chao Lu et al. [13] designed a quadrant detector by quadrant photodiode for estimating the laser beam position. The method used by other researchers to measure the beam size is to place the photodiode or other sensors behind the knife-edge and analyze the size of the laser by receiving the signal behind the knife-edge [14-20]. Our beam profiling system experimental equipment used laser diode package to measure the laser beam size based on the self-mixing interference. Laser diode package is composed of laser diode and photodiode. After the laser emitted from the laser diode package, it hit the knife-edge board, and part of the signal was reflected to the photodiode. The feedback signal received by the photodiode is applied to analyze the beam size. The first advantage of our system is that it is easy to operate. Using the photodiode in the laser diode package could get the beam size of any position during the scan, unlike knife-edge profiler needed moving to collect signal [21-23]. The second advantage is cost affordable. The price of the knife-edge profiler is 10,000 US dollars, while the price of the laser diode package is only 5 US dollars. Based on a $5 laser diode package, accurate beam size can be obtained in an easy way. Moreover, our system is the first to use laser self-mixing interference to preform beam profiling.

This study proposes a novel beam profiling prototype, which uses laser diode package to measure the laser beam size based on the self-mixing interference through the knife-edge approach. The system is composed of laser diode module, galvanometer scanner, galvanometer scanner driver, Arduino, power supply and digital multimeter. The integrated beam size and full width half maximum (FWHM) were calculated, which represent the laser beam size. The meaning of this study is to propose an alternative method for beam profiling, which is easy-to-operate, cost-effective, and yet, being capable to provide accurate beam size measurement.

2. MATERIALS AND METHODS

2.1 Introduction to laser self-mixing interference

Our proposed beam profiling system is based on laser self-mixing interference. Fig. 1(a) is a schematic describing laser self-mixing interference while Fig. 1(b) shows the internal structure of the laser diode package, in which there is a laser diode and a built-in photodiode. The 3 laser diode pins are the laser diode cathode, laser diode anode and photodiode cathode, and photodiode anode, respectively. As shown in Fig.1(a), laser emitted from the laser diode package, passed the lens and shone onto a moving target. A portion of the beam is reflected and transmitted back to the laser diode package via the very same optical track. This feedback laser beam with information of the target then interferes with the laser beam inside the diode cavity where the self-mixing interference occurs, causing a modulation both in amplitude and frequency. Disturbance in the electric field from the re-injected light manifests itself in the variation of laser optical output power, which can then be measured by the built-in photodiode, and used to estimate the target displacement and/ or surface texture.

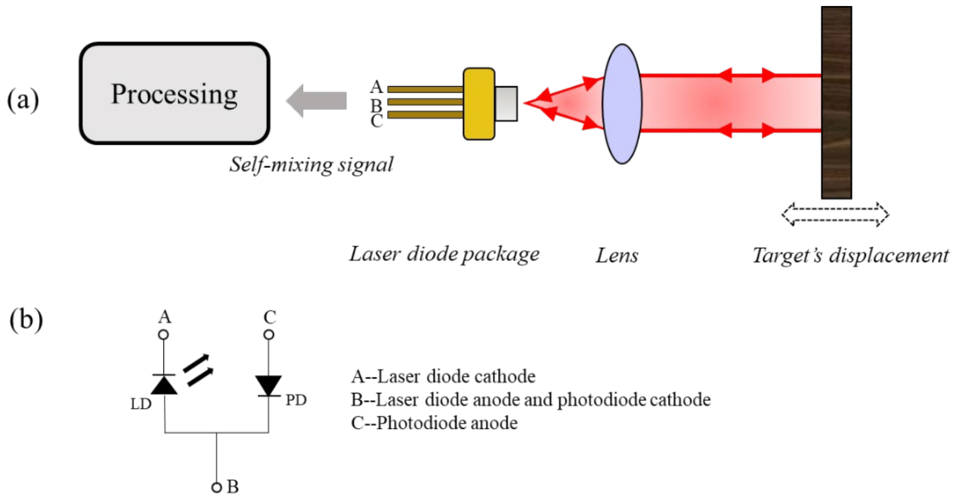


Fig.1 (a) the schematic of the laser self-mixing interference (b) internal structure of laser diode package

2.2 The composition of the beam profiling system

Fig. 2(a) shows that the beam profiling system consists of laser diode module, galvanometer scanner, galvanometer scanner driver, Arduino, power supply and digital multimeter. The function of power circuit was to provide a 20 mA current to laser diode, and it consists of LM317 chip, and resistor. The two pins A and B of the laser diode module are connected to the power circuit, and pin C is connected to the multimeter, which is the output current of the photodiode. The driving circuit is composed of TL082 chip, resistors and capacitors, and outputs a cycle voltage ranging from -2.5 V to 2.5 V under the control of Arduino. The driver circuit is connected to the galvanometer scanner to control the rotation of the mirror.

The wavelength of the laser diode is 650nm, and the power is 7mw. In this experiment, five laser diode modules with different beam sizes are obtained by adjusting the lens to verify the accuracy of the beam profiling system. The TL082 chip needs a supply voltage of plus and minus 12 V. The actual position of each component could be seen from the Fig. 2(b).

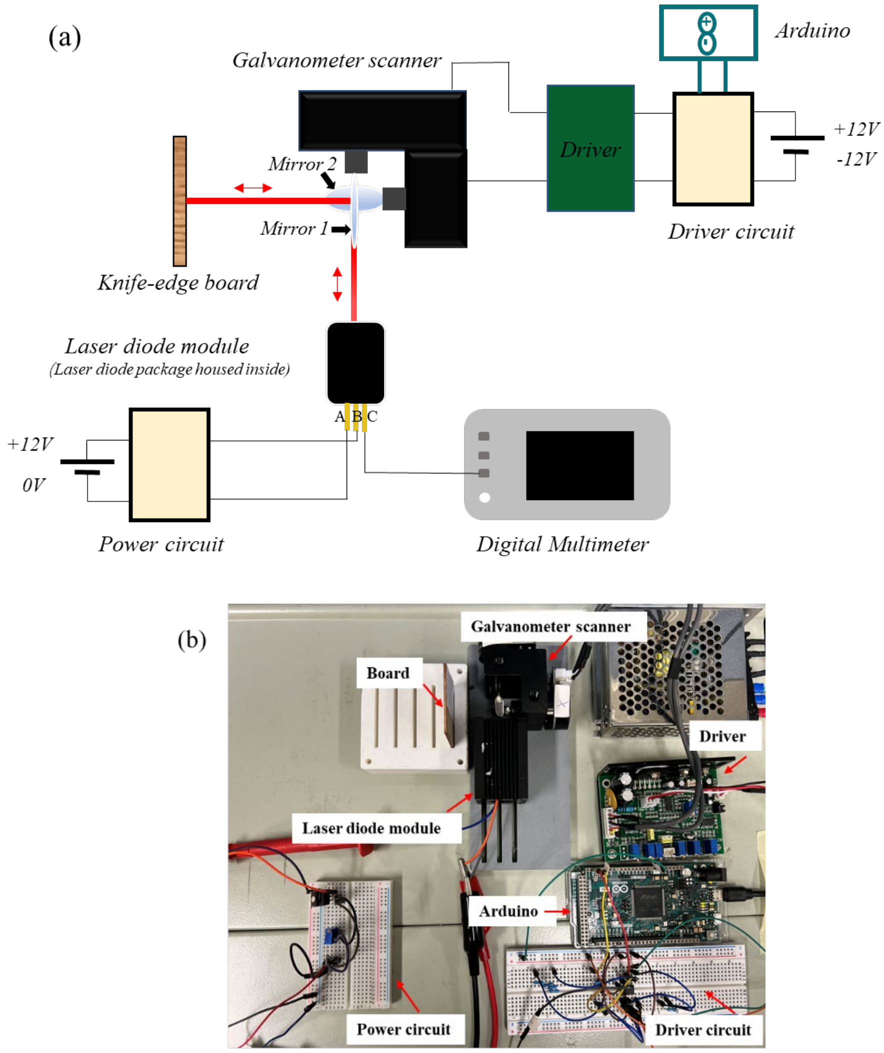


Fig.2 (a) The schematic of the beam profiling prototype (b) The photo of the beam profiling prototype

2.3 Knife-edge board

Fig. 3 presents the scanning directions for obtaining laser beam size. Fig. 3(b) is the picture of knife-edge board. The black and white paper is stitched together to make sure that the knife edge is flat and vertical. Because black absorbs the emitted laser beam and white reflects the emitted laser beam, a knife-edge is automatically formed where the two colors meet. When the laser beam was in the black area, the photodiode received the least feedback signal. As the laser beam moves to the knife-edge, the area of the laser beam falling on the white area is increasing, and the feedback signal received by photodiode will also increase. When the laser beam passes through the knife-edge and is completely in the white area, the photodiode will receive the most feedback signals. In addition, it is necessary to ensure that the beam size is larger than the width of the knife-edge during the measurement process. The moving direction of the laser beam should be perpendicular to the knife-edge.

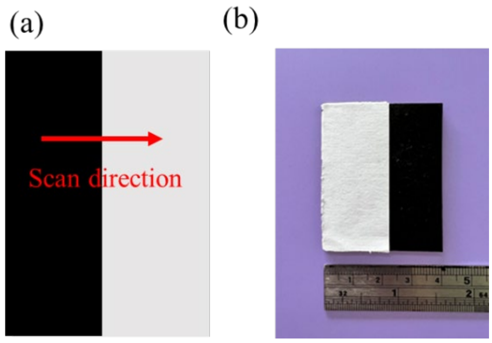


Fig.3 (a) the scan direction to get the beam size (b) the picture of the knife-edge board

2.4 Calculation of optical path

In order to compare the laser beam size measured by the camera beam profiler and the knife-edge experiment, it is necessary to ensure that the distance from the laser diode module to the target is consistent. Fig. 4(a) shows the schematic of laser optical path in the knife-edge experiment. The thickness of the lens (d1) is 3 mm, the distance from the lens to the mirror 1 (d2) is 9 mm, the distance between the centers of the two mirrors (d3) is 6 mm, and the distance between the center of mirror 2 to the knife-edge board (d4) is 20 mm. Fig. 4(b) shows the real distance between the mirror and laser diode module. Fig. 4(c) is the optical path schematic of measuring the laser beam size by the camera beam profiler. The function of the CCD sensor in the beam profiler is to capture the laser beam. The distance from the CCD sensor to the surface of the camera beam profiler (d6) is 12.56 mm. To make the sum of d1, d2, d3, d4 is the same as the sum of d1, d5, d6, the distance from the camera beam profiler to the lens (d5) is 22.44 mm. Fig. 4(d) presents the process of measuring laser beam size through camera beam profiler.

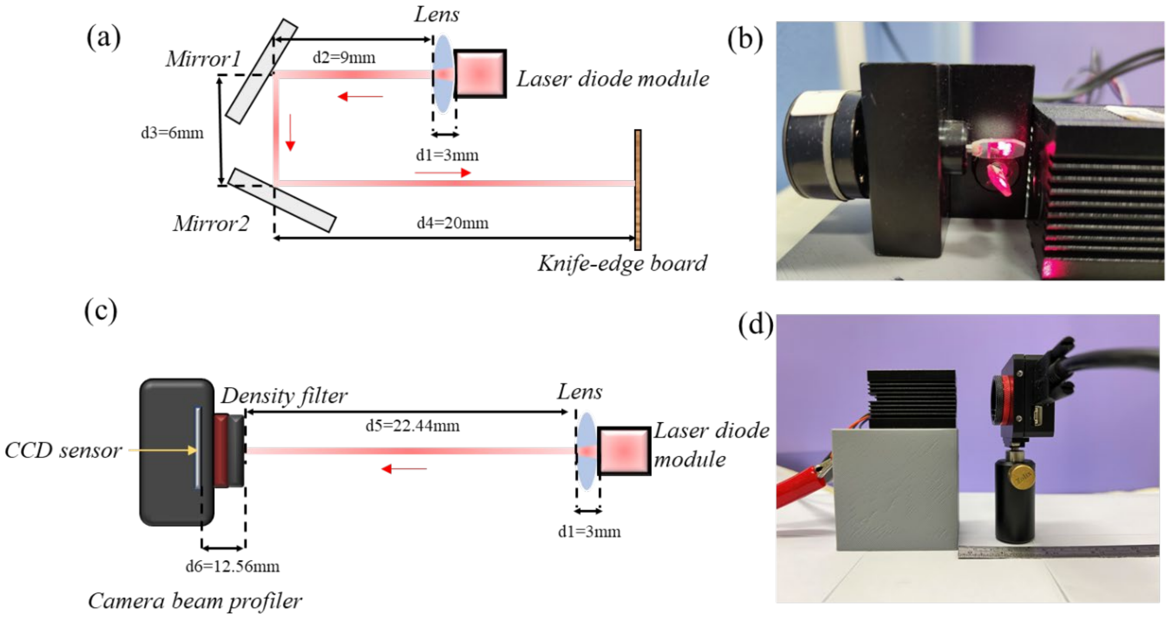


Fig. 4(a) the schematic of laser optical path length (b) the picture of laser diode and galvo (c) the distance between the camera beam profiler and knife-edge board (d) the process of measuring beam size through camera profiler

3. RESULTS

3.1 The shape of the 5 laser diodes module (A-E) through beam profiler

Set up 5 laser diode modules with a series of size gradients, scan the knife-edge board to obtain the laser beam size in the x direction, then compare the full width half maximum (FWHM) with the integrated beam size to evaluate the accuracy of the beam profiling system. Firstly, use the camera beam profiler to obtain the shape and size of the five laser diode modules. Fig. 5 presents the laser beam shape of the five laser diode modules (A, B, C, D, E) from the camera beam profiler. It could be seen that the size of the laser diode modules was increasing from the laser diode module A to E. The five laser diode modules were in an elliptical shape as a whole, and the optical intensity attenuated from the core area to the edge area. According to the intensity distribution shape, it can also be seen that the laser diode module had a Gaussian distribution in the x direction.

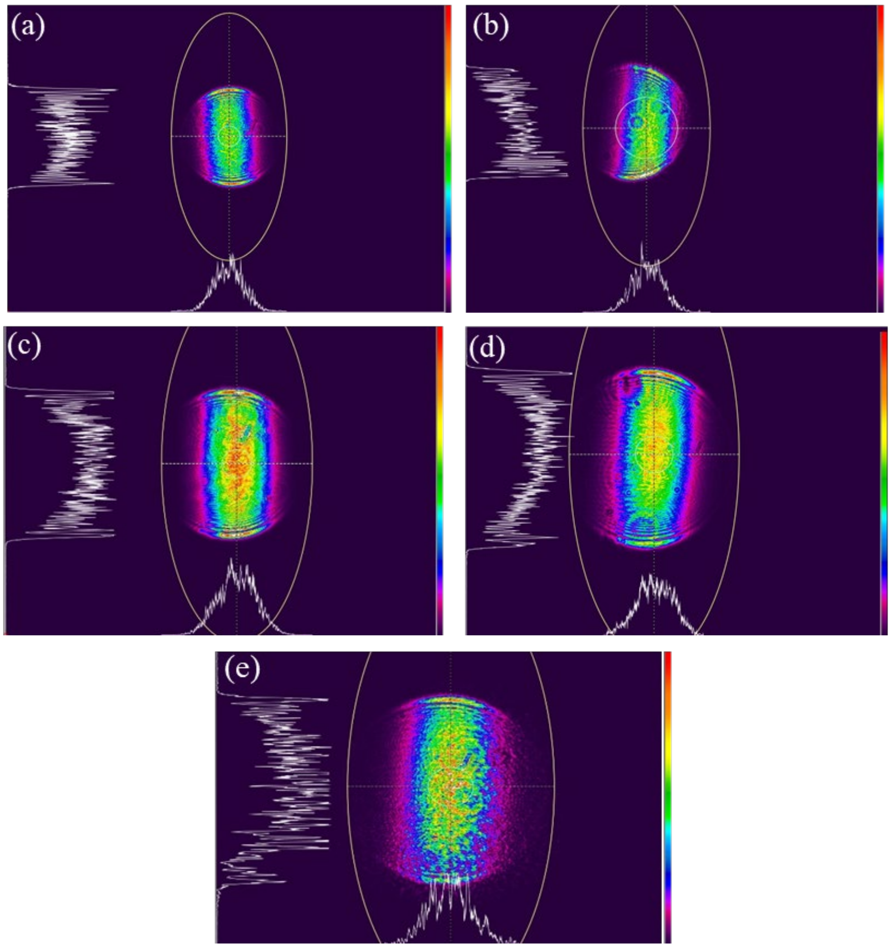


Fig. 5 The shape of the laser diodes module A-E from the camera beam profiler

3.2 Integrated beam size of 5 laser diode modules in x direction

Use formula (1) to fit the raw data to get the best-fitted line, the line is in Gaussian distribution, and use formula (2) to calculate the FWHM, which is the integrated beam size of laser. Fig. 6 show the full width half maximum (FWHM) in x direction of the 5 laser diode modules. The blue lines were the result of adding the optical intensity of each column output by the beam profiler. The red lines were the best-fitted line of the raw data. The integrated beam size of laser diode module A, B, C, D, E in x direction was 0.527 mm, 0.611 mm, 0.715 mm, 0.806 mm, 0.909 mm, respectively.

$$\mathrm{f}\,(\mathrm{x}) = \frac{\mathrm{a}}{\sigma\sqrt{2\pi}}\; e^{\frac{-(x-\mu)^2}{2\sigma^2}} + b \qquad (1)$$

where μ is the mean of the distribution, and σ is the standard deviation of the distribution, a represents the normalization, b represents the off-set of optical intensity.

$$\mathrm{FWHM} = \Delta\mathrm{Img}_{\mathrm{pixel}} \times \mathrm{Width}_{\mathrm{pixel}} \qquad (2)$$

Where ΔImgpixel is the number of pixels between two pixel columns with 25% and 75% of the maximum optical intensity, Widthpixel is the width of pixel (3.45 μm).

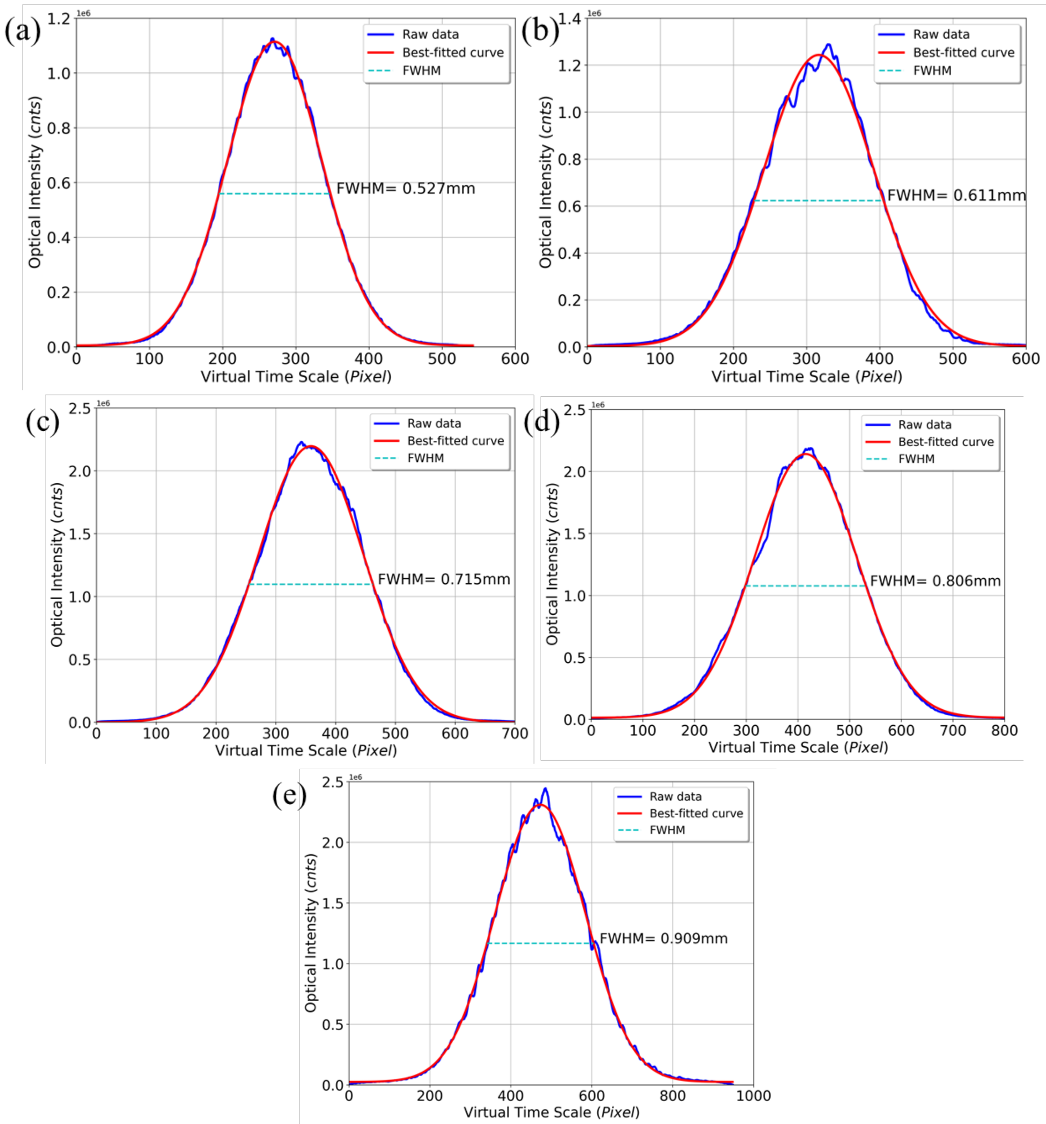


Fig. 6 Integrated laser beam size in x direction of laser diode module A-E

3.3 Knife-edge results in x direction

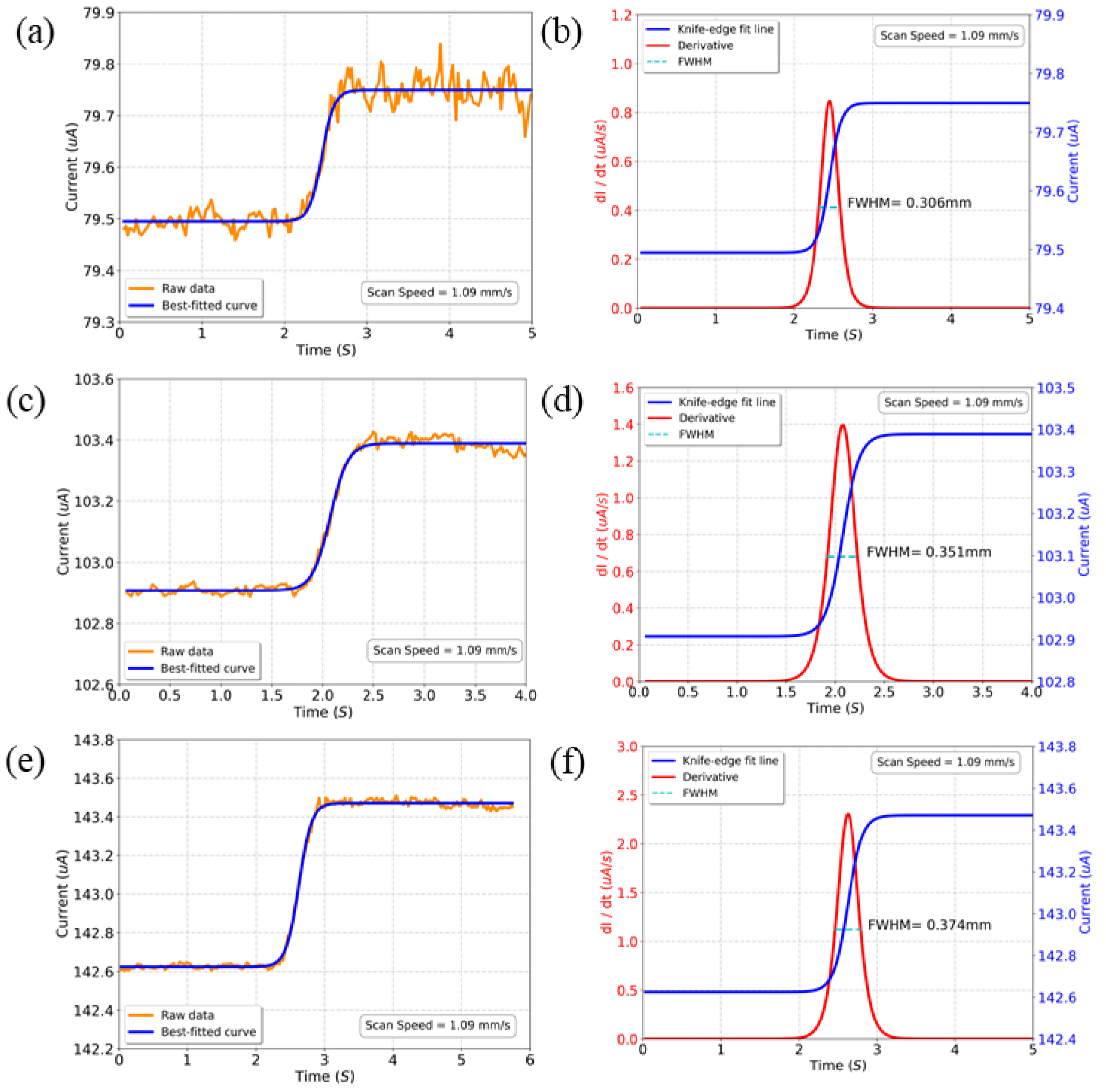
Fig. 7 present the beam size from the beam profiling system by knife-edge approach in x direction of the laser diode module A-E. Fig. 7(a, c, e, g, i) were the raw data from the knife-edge experiment and its best-fitted line. Take Fig. 7(a) as an example, the orange line represents the change in feedback current. When the laser was on the black area on the knife-edge board, the feedback current was 79.50 μA. When the laser was near the knife-edge, the feedback current began to increase. The feedback current rose to 79.75 μA when the laser was completely in the white area. The knife-edge fit line was plotted by fitting the raw data based on formula (3). A, B, x0, and σ1 are the parameters used to modify the standard tanh(x) function. Fig. 7(b) shows the derivation of the knife-edge fit line and the FWHM of laser diode module A. The red line was the Gaussian fit line of the derivative result of the knife-edge fit line, and the FWHM of the derivative line was calculated by formula (4), which was the beam size from the beam profiling system. From Fig. 7(b, d, f, h, j), the beam size from knife-edge scanning of laser diode module A, B, C, D, E is 0.306 mm, 0.351 mm, 0.374 mm, 0.423 mm, and 0.484 mm, respectively.

$$f(x) = A + B \tanh\left(\frac{x - x_0}{\sigma 1}\right) \quad (3)$$

Where A represents the offset in current, B represents the amplification in magnitude, x0 controls the offset in time, and σ1controls the spread of the function.

$$FWHM = \Delta t \times SC \quad (4)$$

Where Δt is the difference of time between two columns with 25% and 75% of the maximum derivation, SC is the scan speed of the laser beam (1.09 mm/s).



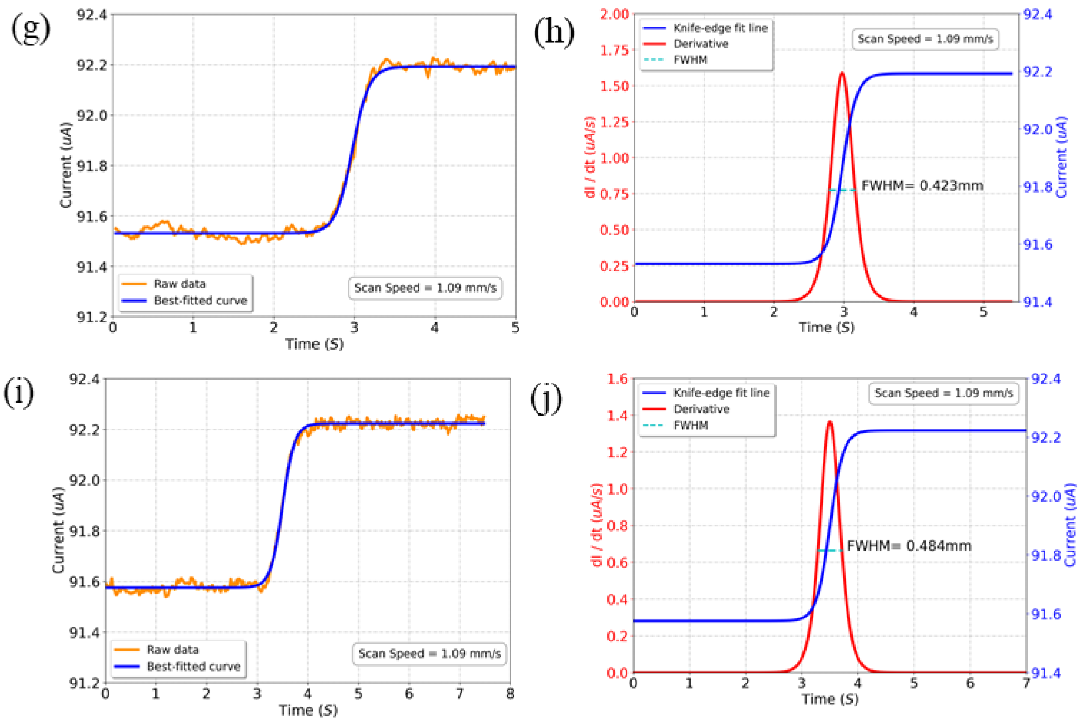


Fig. 7 Beam size from the beam profiling system by knife-edge approach in x direction

Fig. 8 and Tab. 1 compared the integrated beam size from the camera beam profiler and knife-edge results from beam profiling system. It could be seen from Fig. 8(a) that the knife-edge results increased with the laser beam size, but the data obtained from the beam profiling system are all smaller than the data from the camera beam profiler. The variation between the integrated beam size and knife-edge result in x direction of laser diode module A, B, C, D and E is 41.94%, 42.55%, 47.69%, 47.51%, and 46.75%, respectively. The variation did not increase with the laser beam size and remained in a relatively stable range with an average of 45.29%. To illustrate that the knife-edge result is not accidental and to verify the reliability of the beam profiling system, the relationship between the beam size from camera beam profiler and beam profiling system was given in Fig. 8(b). Although the two data are not equal, there was a linear relationship between the beam profiling system and camera beam profiler, which was Y = 2.193 X - 0.136. This linear relationship proved the reliability and stability of the knife-edge results. Based on this linear relationship, could even predict the value in the camera beam profiler through the knife-edge results. As shown in Tab. 2, the predicted beam size of laser diode module A, B, C, D, E is 0.535 mm, 0.633 mm, 0.684 mm, 0.792 mm and 0.925 mm. The error rate between the predicted beam size and integrated beam size is 1.52%, 3.60%, 4.34%, 1.74%, and 1.76%, respectively, indicating the accuracy of predicted beam size is high.

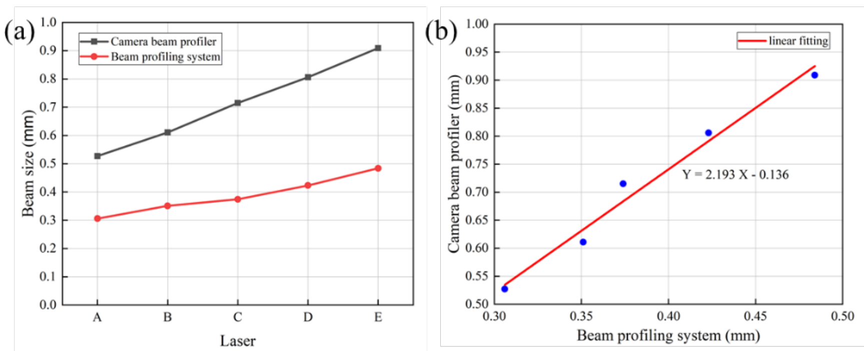


Fig. 8 (a) Trend of the knife-edge result and beam profiler result in x direction (b) Relationship between the knife-edge result and camera beam profiler in x direction

Tab.1 The variation between the integrated beam size and knife-edge result in x direction

	Laser A	Laser B	Laser C	Laser D	Laser E
Integrated beam size	0.527 mm	0.611 mm	0.715 mm	0.806 mm	0.909 mm
Knife-edge results	0.306 mm	0.351 mm	0.374 mm	0.423 mm	0.484 mm
Variation	41.94 %	42.55 %	47.69 %	47.51 %	46.75 %

Tab.2 The error rate between the predicted beam size and the integrated beam size in x direction

Knife-edge results	0.306 mm	0.351 mm	0.374 mm	0.423 mm	0.484 mm
Predicted beam size	0.535 mm	0.633 mm	0.684 mm	0.792 mm	0.925 mm
Integrated beam size	0.527 mm	0.611 mm	0.715 mm	0.806 mm	0.909 mm
Error	1.52 %	3.60 %	4.34 %	1.74 %	1.76 %

4. DISCUSSION

Table 2 show that our self-mixing knife-edge measured beam size (FWHM) of the Gaussian-like beam are smaller than that obtained from the camera beam profiler by 45.29 % on average. This result is believed to be related to the amount of laser beam back-reflected into the laser diode cavity. This shows that, our self-mixing beam profiling prototype could not capture all the forward-shining laser beam owing to specular and diffuse scattering. Only a portion is back-reflected into the laser diode package cavity. Moreover, high power laser diode packages received more feedback beam after diffuse reflection and specular reflection, while low power laser diode packages received less feedback beam, all laser diode packages used in this study are only at 7 mW. The back-reflected laser power was expected to be low – on the level of the order of 0.07-0.7mW (typical back-reflected power is in the range of 0.01-10% of the total laser optical power [24]).

5. CONCLUSION

In this study, a novel beam profiling system based on self-mixing interference was developed to measure the Full Width Half Maximum of 5 laser diode packages with different size by knife-edge approach. The first advantage of beam profiling system is that it is easy to operate. Using the photodiode integrated in the laser diode package could get the beam size at any position, unlike knife-edge profiler needed to be moved to collect signal. The second advantage is cost affordable. The price of the knife-edge profiler is 10k US dollars, while the price of the laser diode package is only 5 US dollars. Moreover, this is the first time to use laser self-mixing interference to do beam profiling. The results proved that there is a linear relationship between the knife-edge results of Gaussian-alike beam and integrated beam size from camera beam profiler, and the average variation between the knife-edge results of Gaussian-alike beam and integrated beam size is 45.29%. Our system could provide an accuracy predicted beam size according to the linear relationship. However, in order to narrow the variation in knife-edge results and integrated beam size, laser diode package with higher power and different shapes need to be carried out in the future. It is believed that this study has contributed to the on-going development of beam profiling, providing an alternative method to measure the laser beam size.

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REFERENCES

[1] Makarov, G N. Laser applications in nanotechnology: nanofabrication using laser ablation and laser nanolithography. Physics Uspekhi, 2013, 56(7):643-682.

[2] Schwarz F, Aoki A, Becker J, et al. Laser application in non-surgical periodontal therapy: a systematic review. Journal of clinical periodontology, 2008, 35: 29-44.

[3] Ion J. Laser processing of engineering materials: principles, procedure and industrial application. Elsevier, 2005.

[4] Bachmann F G. Industrial laser applications. Applied Surface Science, 1990, 46(1-4): 254-263.

[5] Siegman A E. Defining, measuring, and optimizing laser beam quality. Laser Resonators and Coherent Optics: Modeling, Technology, and Applications, 1993, 1868: 2-12.

[6] Mccabe G. Measurement of the μm sized radius of Gaussian laser beam using the scanning knife-edge. Appl Opt, 1975, 14(12):2809-2810.

[7] Kwon J, Mayerich D, Choe Y. Automated cropping and artifact removal for knife-edge scanning microscopy// IEEE International Symposium on Biomedical Imaging: from Nano to Macro. IEEE, 2011.

[8] Handa S, Kimura T, Mimura H, et al. Extended knife-edge method for characterizing sub-10-nm X-ray beams. Nuclear Instruments & Methods in Physics Research, 2010, 616(2-3):246-250.

[9] Brakenhoff G J, Blom P, Barends P. Confocal scanning light microscopy with high aperture immersion lenses. Journal of Microscopy, 1979, 117(2).

[10] Haumann C, Pelargus C, Frey H G, et al. Stand-alone device for the electrolytic fabrication of scanning near-field optical microscopy aperture probes. Review of Scientific Instruments, 2005, 76(3):651.

[11] Riel M, Laurin J J. Design of an Electronically Beam Scanning Reflectarray Using Aperture-Coupled Elements. IEEE Transactions on Antennas & Propagation, 2007, 55(5):1260-1266.

[12] Purvis K, Cisek R, Tokarz D. New Activity for Instrumental Analysis: Laser Beam Profiling. Journal of chemical education, 2019.

[13] Chao, Lu, Yu-Sheng, et al. A novel method to improve detecting sensitivity of quadrant detector. Optik - International Journal for Light and Electron Optics, 2014, 125(14):3519-3523.

[14] Itamiya H, Kubo M O, Sugita R, et al. New method of structural analysis and measurement of V-shaped percussion cracks in quartz sands surface by confocal laser scanning microscope (CLSM). Micron, 2022, 153:103174-.

[15] Fahmy A A, Zhang J, Wang X, et al. Practical consideration for 4-beam laser interference lithography process. 2007.

[16] Lebental B. Controlled, Low-Temperature Nanogap Propagation in Graphene Using Femtosecond Laser Patterning. Small, 2018, 14(31).

[17] Akhtar S S. Laser cutting of circular holes in AISI 304 stainless steel sheet: Heating, diffusion and stress analyses. Lasers in engineering, 2016(34-4/6).

[18] Ramesh S. Modeling and Detecting Damage in Rails & Avoidance of Collision in the Tracks. 2013.

[19] Dearden G, Sharp M, French P W, et al. Initial studies of laser beam performance monitoring using a novel camera-based in-line beam monitoring system// ICALEO® 2001: Proceedings of the Laser Materials Processing Conference and Laser Microfabrication Conference. 2001.

[20] Catani L, Cianchi A, Pirro G D, et al. A large distributed digital camera system for accelerator beam diagnostics. Review of entific Instruments, 2005, 77(7):93301.

[21] Pda B, Eea B, Msa B. Camera-based closed-loop control for beam positioning during deep penetration welding by means of keyhole front morphology - ScienceDirect. Procedia CIRP, 2020, 94:758-762.

[22] Shengwei, Ren, Shiping, et al. A new track inspection car based on a laser camera system. Chinese Optics Letters, 2011.

[23] Itoh H, Mukai S, Yajima H. Optoelectronic fuzzy inference system based on beam-scanning architecture. Applied Optics, 1994, 33(8):1485-90.

[24] Liu Z, Gu W. High-speed and high-precision deflectors applied in electron beam lithography system based on scanning electron microscopy. Journal of Vacuum Science & Technology B Microelectronics and Nanometer Structures, 2004, 22(6):3557-3559.