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Optical power independent optical beam profiler

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Abstract. To the best of our knowledge, proposed and demonstrated for the first time is an optical power independent optical beam profiler instrument. The instrument uses a pair of symmetrically located power detection photodetectors along with an electronically programmed two-dimensional digital micromirror device to implement spatial beam profiling. The instrument also features high-repeatability all-digital controls and fast millisecond reconfigurations. The instrument can have a critical impact in test, measurement, and monitoring systems for various optical beams, including high-power laser beams. [DOI: 10.1117/1.1651557]

Subject terms: spatial beam profiling; high optical power; micromirror devices.

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1 Introduction

Optical beam profiling is a spatial beam measurement technique that provides the power distribution information across a two-dimensional (2-D) slice of the optical radiation. Knowledge of this spatial information is critical across many fields of science and engineering where a particular optical beam spatial profile is necessary to accomplish the system function. In particular, this spatial information is important while operating high-power laser beams where changes in beam profiles can lead to errors such as in applications involving laser cutting and parts machining. Today, commercial optical beam profiling is done via two dominant means. The first method uses a 2-D sensor such as a charge-coupled device (CCD) to snap at video rate a power profile of the directly incident beam.[1] This method is suited for low (e.g., submilliwatt) power beams as CCDs easily saturate. Although attenuators can be used before the CCD to reduce the light power level, high-power laser beams can introduce thermal lensing effects in the attenuators, causing changes to the original beam profile, hence giving erroneous measurements.[2] Similarly, any beam splitting optics placed in the beam path for power level calibration can lead to spatial beam spoiling such as aberrations that can also lead to incorrect spatial power maps. The more common and tested method that can handle high (e.g., watt level) power optical beams is the method based on mechanical profilers.[3–6] Specifically, these profilers use a moving element such as a knife edge, pinhole, or slit that is scanned across a beam profile while simultaneously taking transmitted light optical power measurements. In this case, an attenuator can be placed between the mechanically moving aperture (spatial region under test) and the optical power meter as spatially integrated total power is the key measurement that later allows the calculation of the spatial beam profile. A common mechanical profiling approach is the moving knife-edge method that generates an error function relationship between the power measured and the position of the knife edge for the given beam profile.[7] Analysis of the error function is then used to calculate the given beam profile such as the beam waist of a Gaussian beam.

An important requirement for the mentioned and other proposed profiling methods[8–11] to date is that while the profiling operation is being conducted, the optical beam must maintain a fixed or constant power level. If for instance the laser power fluctuates during the profiling operation, the profiler is no longer calibrated, and erroneous beam profile data is generated. There are many scenarios where the laser beam power undergoes unwanted power fluctuations such as during laser fabrication and testing or during long-term laser operations with changing operational conditions, man-made or environmentally invoked. Thus, it would be highly desirable to develop an optical beam profiler instrument that is insensitive to the incident optical power. In this paper, to the best of our knowledge, for the first time such an incident power independent beam profiler is proposed and demonstrated.

Earlier, we introduced the concept of all-digital fiber-optical variable attenuation where any desired optical power attenuation level can be generated by selectively controlling an array of digital micromirrors illuminated by an optical beam of known spatial beam profile.[12–14] If one now applies this digital variable attenuator principle in reverse, i.e., by selectively controlling the array of digital micromirrors, optical power measurements can be taken that can determine the unknown spatial profile of the illuminating beam, the principle of the all-digital beam profiler is realized. To prove the mentioned concept of a digital microelectromechanical system (MEMS)-based beam profiler, implementation of the classic moving knife-edge technique for spatial beam profiling has been successfully performed in both the visible[15] and infrared (IR) bands[16] using a Digital Micromirror Device (DMD™) from Texas Instruments (TI). These experiments successfully proved the versatility of the digital profiler for testing beams with constant powers. Next, as shown in this paper, the digital MEMS profiler can be simply yet critically modified to realize an all-powerful instrument that works equally well with beams of changing incident optical powers. The rest of the paper describes the design of the proposed profiler, its

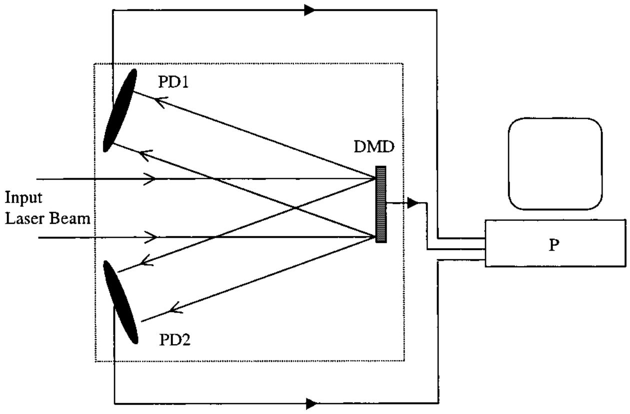

Fig. 1 Proposed power independent optical beam profiler. DMD™: Digital Micromirror Device; PD1 and PD2: large area photodetectors; P: processor such as digital computer.

experimental results proving its power independent performance, and issues related to system design.

2 Power Independent Profiler Design

Figure 1 shows the proposed power independent optical beam profiler. Here, light to be spatially characterized is normally incident on the DMD™ surface. As was explained in our earlier work, the DMD™ can be programmed to generate any desired moving mechanical element by simply setting the states of the micromirrors in the device. Specifically, each micromirror has two states of operation: $+\theta$ and $-\theta$ mirror positions. θ for the IR TI DMD™ is 9.2 deg and for the visible TI DMD™ is 10 deg. As shown in Fig. 1, when the desired micromirrors across the test beam area are set to $+\theta$ position, the corresponding part of the optical beam is reflected to the photodetector PD1 and a power reading P1 is taken. Simultaneously, the remaining part of the device is set for $-\theta$ micromirror position and hence this part of the optical beam is reflected toward the second photodetector PD2 that takes a power reading P2. The detector placement is symmetric with the incident beam and device location, with reflected beams offset by 2θ about the axis. At any given instant of the profiling operation when PD1 and PD2 simultaneously take power level readings integrating photons for a preset equal integration time, the total power P1+P2 becomes the required power normalization factor for that specific reading. Any laser power fluctuations within the two power meter integration times equally scales both power meter readings. Hence, the P1 and P2 readings can be normalized for each profiler data acquisition setting. This is done by dividing P1 and P2 by P1+P2 to implement the desired electronic processing. In this way, incident beam power fluctuation effects can be negated while processing the optical power data to generate the desired incident beam spatial profile. Note that similar to current commercial mechanical profilers designed for high-power spatial beam profiling, the power meters in the proposed profiler can be operated with adjustable attenuators attached to the photodetector heads. More importantly, unlike current mechanical profilers that operate in a transmission-only light mode with a single power meter that makes it impossible to operate in a power independent mode, the proposed digital MEMS profiler operates in the critical reflective two-deflection-state mode (i.e., each micromirror operates in two equal angle tilt states along the beam optical axis). This symmetric two-port design then allows simultaneous power measurements required for true instantaneous laser power independent profiling. Next, a proof-of-concept experiment is performed to demonstrate the proposed power independent beam profiling.

3 Experiment

Because all micromirrors on the DMD™ are arranged in 2-D space and the desired micromirrors can be tilted to the $+\theta$ or $-\theta$ mirror position, the motion of mechanical elements such as the moving knife edge, the scanning slit, the scanning pinhole, and the variable aperture can be simulated via software programming of the DMD™. For the experiment, a Gaussian beam of a 0.6-mm $1/e^2$ beam diameter exits a fiber lens coupled infrared 1550-nm laser that is used as a light source. The classic moving knife-edge technique for spatial beam profiling is performed on this Gaussian beam using the IR DMD™ profiler. Note that the resolution of the optical beam profile measurement is limited by the pixel pitch in the DMD™, e.g., 13.8 μm for IR DMD™. For executing knife-edge beam profiling, a row or column of micromirrors are flipped from one θ setting to the other in succession thus simulating a moving knife edge. The optical energy deflected by these micromirrors forming two segmented sections of the cutting knife edge are simultaneously captured by PD1 and PD2. For our experiment, a vertical knife edge is implemented as follows. First, all micromirrors are set to the $+\theta$ state (light reflected to PD1), and then the number of $-\theta$ state micromirrors (light reflected to PD2) along the x axis is increased. The result of this knife edge sliding across the cross-sectional area of the Gaussian optical beam along the x axis gives the relationship between the PD1 photodetected normalized optical power $P_1 = \mathrm{P1}/(\mathrm{P1}+\mathrm{P2})$, and the position of the knife edge "x_0" as

$$P_1 = \mathrm{erf}[\sqrt{2}x_0/w_x(z)], \tag{1}$$

where erf(c) represents the error function of c, and $w_x(z)$ is the optical beam radius at the location "z" corresponding to the profiling plane along the optical axis. The expression of the normalized optical power $P_2 = \mathrm{P2}/(\mathrm{P1}+\mathrm{P2})$ for PD2, which is complementary to Eq. (1), can be written as:

$$P_2 = 1 - \mathrm{erf}[\sqrt{2}x_0/w_x(z)]. \tag{2}$$

Using either Eq. (1) or Eq. (2), the desired beam waist radius of the Gaussian beam under test is calculated.

As a first step for referencing the profiler measurement, profiling using the Fig. 1 system is implemented using a fixed-power stable 1550-nm laser. Figure 2 shows the normalized error function obtained for this scenario using PD1. This data indicates a measured Gaussian beam waist radius $w(z)$ of 0.394 mm that now serves as a reference measurement. Note that data taken via PD2 also gives the same beam waist result, a result expected from the symmetric design and operations of the Fig. 1 profiler.

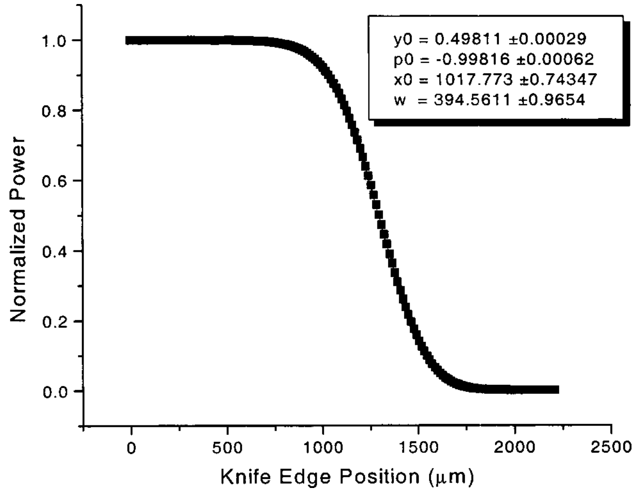

Fig. 2 The normalized error function obtained via the Fig.1 system using PD1 and a fixed incident optical power from the laser source. The data indicates a 0.394-mm Gaussian beam waist for the incident beam. This data serves as the reference test data.

Next, Fig. 3 shows the raw error function data obtained using a laser with a 70% power fluctuation. Specifically, this fluctuation is deliberately introduced by tuning the laser power to a given value for each set of power meter readings. The data shows three curves for the detected power level. One curve shows raw power detected from PD1 versus knife edge position, another shows the complementary error function generated from data taken via PD2, and finally the third curve indicates the sum power or P1 + P2 as the DMD™ generated knife-edge position changes. Hence, this third curve shows that indeed the total detected laser power also fluctuates over a 70% range of the initial laser power. As seen in Fig. 3, laser power fluctuations lead to spoiled error functions that cannot give accurate readings for the profiled laser beam.

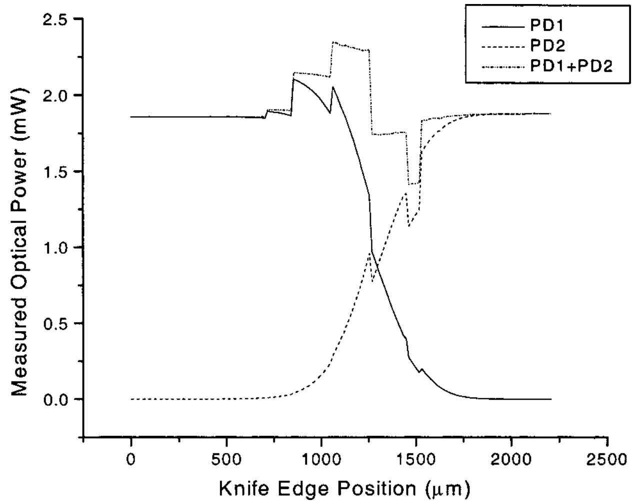

Fig. 3 Measured optical power of the fluctuating laser source versus knife edge position for PD1, PD2, and PD1 + PD2. The PD1 and PD2 generated curves indicate poor error function fits due to the power fluctuations during the beam profiling process.

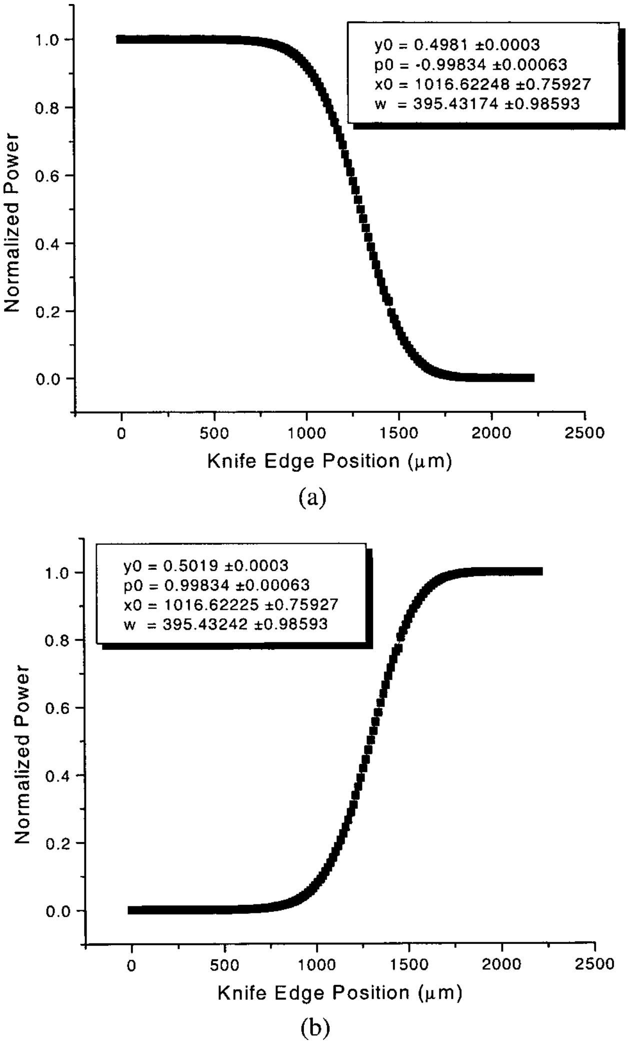

Fig. 4 Normalized power of the fluctuating source versus knife edge position data for (a) PD1 and (b) PD2, showing excellent error function fits. Normalization is done with the sum of the two photodetector readings (PD1 + PD2). The beam waist numbers generated by normalized processing data from PD1 and PD2 are 0.395 mm and 0.395 mm, respectively.

Figure 4 shows the corrected or normalized beam profiling data where the raw data from Fig. 3 was normalized using the PD1 and PD2 readings. As shown, this normalized data has recovered the original (stable laser power) error function, leading to a near 100% fit with the Fig. 2 data. Figure 4 data, either from PD1 [Fig. 4(a)] or PD2 [Fig. 4(b)] indicates a beam radius of 0.395 mm. The earlier reference data from Fig. 2 when a stable laser was used indicated the beam to have a 0.394-mm beam waist at the DMD™ measurement plane. Hence, a near-perfect measurement recovery with 0.25% accuracy has occurred with the proposed profiler of Fig. 1 when the correct electronic post processing is used. Note that the distance from the DMD™ to each photodetector is 30 cm and the photodetectors had an active area of 3 mm diameter. Also note that the IR TI DMD™ is an ultrastable device where the tilt micromirrors, once set to their binary states, stay in fixed positions and hence do not introduce any temporal noise into the proposed profiler measurement system.

The IR TI DMD™ has been designed as a high-diffraction-efficiency blazed grating for 1550 nm given the $13.8\ \mu m \times 13.8\ \mu m$ micromirrors with ± 9.2-deg tilt angles.[17] To reduce interference effects, the device has a 1550-nm band IR coated hermetic glass window. The overall measured DMD™ optical loss is 1.9 dB where a small 0.8-dB loss is due to diffraction while the remaining loss is via effects such as device fill factor, coating of hermetic glass window, and micromirror reflectivity. Thus, as desired the majority of the incident laser power is directed to the two symmetrically located photodetectors. Because of the square geometry of the micromirror structure and the overall 2-D pixel layout symmetry, the light loss due to diffraction during the laser beam profiling process acts as a symmetric scaling factor for both photodetector measurements, hence leading to accurate profiling measurements. An important parameter for the DMD™ when used within the proposed profiler is its response to various environmental effects such as temperature and mechanical fatigue. Recently, extensive tests have shown the DMD™ is indeed an environmentally robust device with greater than 100,000 operating hours and more than 1 trillion mirror cycles.[18] The device works effectively with high-power beams such as with 5-W (1-mm-diameter) continuous-wave argon ion lasers. In addition, the device has shown excellent thermal properties considering it has been used for movie cinema projection where hundreds of watts of white light strike the DMD™ surface.

4 Conclusion

To the best of our knowledge, the first incident power independent direct measurement optical beam profiler has been proposed and demonstrated. A simple yet powerful modification to our earlier proposed all-digital profiler allows this new highly desirable feature so far elusive in profiling instruments. The proposed profiler exploits reflective two-port operation possible via only one 2-D digital micromirror array working in unison with a pair of photodetectors (or power meters). This profiler can usher in a new age of incident power independent optical beam profiling, particularly for high-power applications. The proposed instrument also has other attributes such as broadband (visible, IR) operations, large 10.5-mm-diameter optical incidence area, small (e.g., $13.4\ \mu m$) spatial resolution, all-digital repeatability and reliability, and fast multiple mechanical beam profiling techniques within one cost-effective unit. The fast programmable nature of the proposed profiler (each micromirror can be set in $15\ \mu s$) can also find applications in adaptive laser beam control applications. In addition, optical beam image spatial partitioning techniques borrowed from digital image processing methods can be implemented via the proposed profiler to enhance measurement accuracy while improving processing times. By translating the profiler along the laser beam optical propagation axis, true three-dimensional spatial power distribution information can be generated leading to accurate beam propagation characterization and measurements.

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