The NU-POWER all-digital beam profiler: a powerful new tool for spatially characterizing laser beams

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The NU-POWER^{TM} All-Digital Beam Profiler – A Powerful New Tool for Spatially Characterizing Laser Beams

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ABSTRACT

An all-digital laser beam profiler instrument is proposed and demonstrated that for the first time can provide real-time and full-repeatability multi-technique profiling with high power (e.g., > 10 kW/cm^2) laser beams.

1. INTRODUCTION

There are a wide variety of laser-based activities requiring precise and repeatable laser beam profiling, particularly at high power levels. Today, high power laser beam profiling is done by moving knife-edge or moving pin-hole methods that require accurate analog-mode translation of a mechanically moved element. This in-turn leads to serious beam profiling limitations in terms of speed, accuracy, and repeatability of measurement. Moreover, the slow speed nature of the instrument leads to higher susceptibility to mechanical vibrations, which forces the instrument to be large and bulky. Note that general photodetector based profilers cannot be used for direct profiling of high power laser beams as for instance the charged coupled devices (CCDs) for imaging suffer saturation effects. Moreover, use of additional attenuation optics with the laser beam alters the real beam properties, such as via thermal lensing effects at higher powers. Because, many military and commercial systems use high power (e.g., > 10 mW CW) laser beams, there is an enormous need to realize a highly reliable, compact, real-time, low cost, highly repeatable optical beam profiler.

2. THE ALL-DIGITAL BEAM PROFILER: THE SHIFT TO THE ALL-DIGITAL PARADIGM

So far, to the best of the author's knowledge, the mentioned desired high optical power handling beam profiler instrument is yet to be proposed and demonstrated. This paper describes the NU-POWER^{TM} series beam profiler, a unique beam profiler design that can realize the difficult high laser power beam profiling mission. The proposed patent pending fully programmable profiler achieves the difficult mission by using highly reliable all-digital micro-mirror device technology in combination with simple high dynamic range photodetection optics to provide the desired wide optical spectrum, polarization independent, all-digital, high repeatability, high speed beam profiling. NU-POWER^{TM} is a new kind of fully programmable optical beam profiler that can solve the limitations of the existing high power optical beam profilers. Specifically, this paper proposes an all-digital beam profiler where the actual motion of the scanning elements is digital and the complete beam aperture scan operation is also digital. Moreover, all the control electronics for the mechanical scan is also digital.

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 [1]. 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. In essence, the working basics of the proposed digital profiler incorporates the basic principles behind the two dimensional (2-D) photodetector array and mechanical scanning profiling techniques within a digital paradigm, leading to the implementation of a digitally controlled and implemented mechanism that robustly simulates the moving mechanical elements required for accurate beam profiling. In effect, the cooperation between an array of 2-D small tilt micromirrors and a highly sensitive photodetector inherently forms the 2-D photodetector array-based optical beam profiler.

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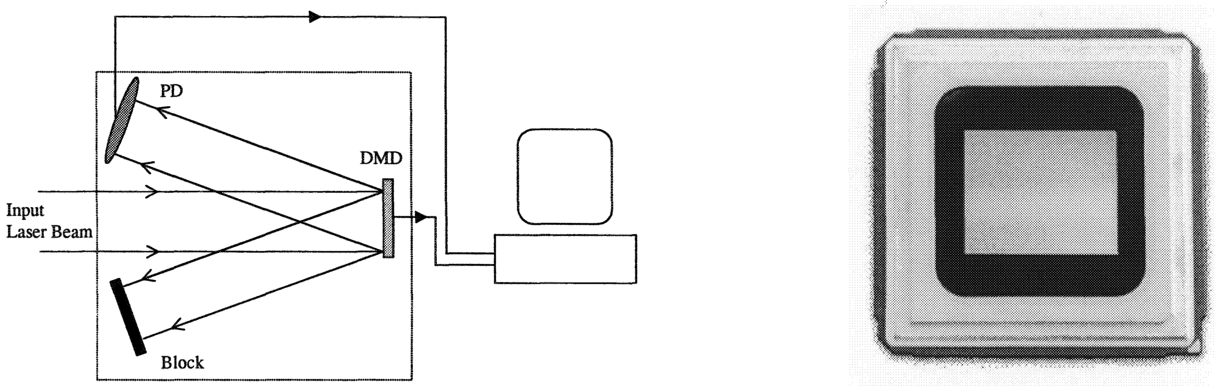


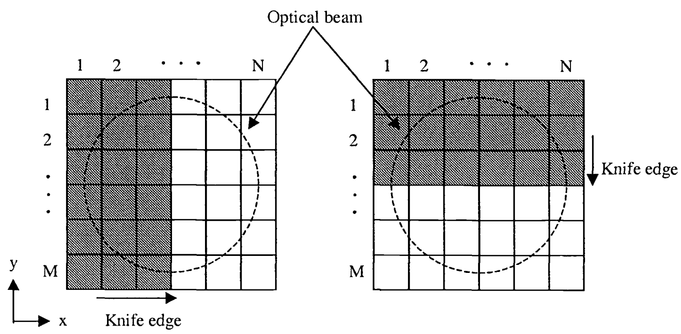
Fig.1 (a) The basic structure of the proposed all-digital optical beam profiler using a two-dimensional (2-D) small tilt micromirror device, a large area photo-detector (PD), and a computer.n (b) 2-D micromirror array chip in the NU-POWER™ profiler using the proven DLP™ Technology from Texas Instruments (TI).

NU-POWER™ optical beam profiler offers [2-3] the world's first high power handling profiler based on optical Microelectromechanical Systems (MEMS) technology. Our profiler uses the proven DLP™ Technology from Texas Instruments (TI) for the 2-D micromirror array chip. This versatile profiler system can be electronically programmed in real-time to implement several known mechanical moving part profiling techniques such as moving knife edge, slit, pin-hole, etc., to generate multiple beam profile measurements leading to highly reliable and accurate beam data. The unit features an intrinsic all-digital design for the moving parts, providing unprecedented digital repeatability and reliability for the measurement across broad spectrums and beam areas.

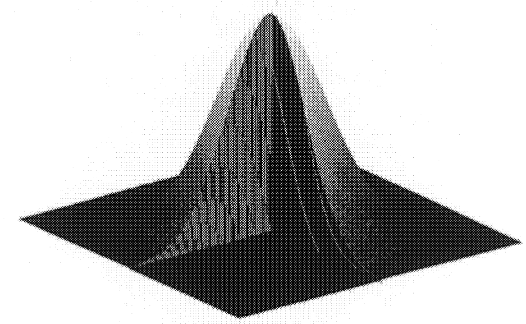
The basic simple structure of the all-digital optical beam profiler is shown in Fig.1 where only one 2-D small tilt digital micromirror device (or DMD™) and one large area photodetector with processing electronics are the key components to generate moving mechanical part beam profiling techniques. Each micromirror has two states of operation: $+\theta$ and $-\theta$ mirror positions. θ for the IR TI DMD™ (see Fig.1 (b)) is 9.2 degrees and for the visible TI DMD™ is 10 degrees. From Fig.1, when the desired micromirrors are set to $+\theta$ position, the corresponding part of the optical beam is reflected to the photodetector and a power reading is taken. On the other hand, the optical beam is directed to the absorber when the specified micromirrors are set to $-\theta$ position. It can be seen that each micromirror is equivalent to one pixel of the 2-D photodetector array. Hence, a 2-D photodiode array-based optical beam profiler is inherently formed. In addition, because all micromirrors 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™. Note that the resolution of the optical beam profile measurement is limited by the pixel pitch in the DMD™, e.g., 13.8 microns for IR DMD.

3. INFRARED BAND PROFILER BASIC EXPERIMENTAL DEMONSTRATION

To prove the concept of a digital MEMS-based beam profile measurement, the implementation of the moving knife edge technique for spatial beam profiling is performed. Initial profiler experiments in the visible band using a visible DMD™ have shown promising results [2]. Here, infrared (IR) operation with an IR DMD™ profiler is described. A DMD™ has a 2-D array of small tilt micromirrors. For 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 is absorbed. The remaining energy is captured by the photo-detector and noted. A vertical and a horizontal knife edge simulated by flipping the micromirrors in groups are shown in Fig. 3(a) .The same concept can be extended to simulate moving slit, pinhole and variable aperture methods.



(a)



(b)

Fig.3 (a) Method to create a moving knife-edge on the DMD™, (b) 3-dimensional beam profile constructed from 2-dimensional knife edge measurement data. Pixel Pitch: 13.8 micron. Laser Beam Wavelength: 1550 nm.

The measured data from any of the methods implemented by using the TI DMD™ can then be used to calculate the beam parameters like beam width, ellipticity, and beam divergence. 2-D and 3-D profiles and reconstructions can be plotted and analyzed. A 3-D reconstruction of the beam profile using the MEMS profiler is shown in Fig.3(b). This beam has a 0.48 mm FWHM measured using the knife edge method on the digital profiler with mathematical operations explained earlier [2]. The tested MEMS profiler gave a low 0.6% measurement error versus the measurement taken with a 10 micron precision manual knife edge profiling method.

4. HIGH RESOLUTION PROFILER DESIGN: AN EXTENSION

For the proposed all-digital profiler, it would be highly desirable to reduce the digital motion limitations that limit resolution to the digital physical step of the mechanical element such as knife edge or slit. Furthermore, it would be useful to introduce new beam profiling methods that take full advantage of the complete micromirror or pixel programmability of the 2-D pixelated device, leading to a higher resolution beam profile measurement. It is the object of this section to introduce a combined digital-analog controlled optical beam profiler that uses as the preferred design, an array of 2-D small tilt micromirrors in combination with an analog fine motion of the 2-D chip with motion in the x and y directions within a pixel range [3]. Because small pixel range chip motion in x and y is required for the proposed invention, only small distances are traveled which means that fast translation can be achieved. This is unlike other motion methods where translation over the whole beam aperture is required that can take a long time. As a preferred design, the small tilt micromirror device is based on the mature MEMS technology that offers low cost compact mechanical elements with low electrical analog/digital drive control via the use of low cost batch fabrication techniques similar to semiconductor electronic chip production methods. The chip x-y analog motion can be implemented via a number of electrically actuated mechanisms such as piezoelectric stages, MEMS actuator-based stages, magnetically controlled stages, etc. In general, any 2-D multi-pixel transmissive/reflective/absorptive device can be used in the proposed optical beam profiler. As the size of the pixels in the MEMS chip/DMD is fixed, there is a lower limit on the step size and hence the resolution in the all-digital beam profile measurement. This lower limit can be further lowered by subdividing the pixels into smaller sample points. This is achieved by displacing the DMD chip by a know distance within a pixel pitch in its plane and repeating the beam profile measurement. Then by using the data taken at different chip position, the power at the sub-pixel level can be calculated mathematically, leading to a high resolution profile map. In another embodiment, a new profiling method is proposed in which a variable width slit and an inverse variable size pin-hole (variable size black spot) are used in conjunction to give highly accurate measurement of the beam profile. This method eliminates and in some cases reduces the need of using optical attenuators at the detector.

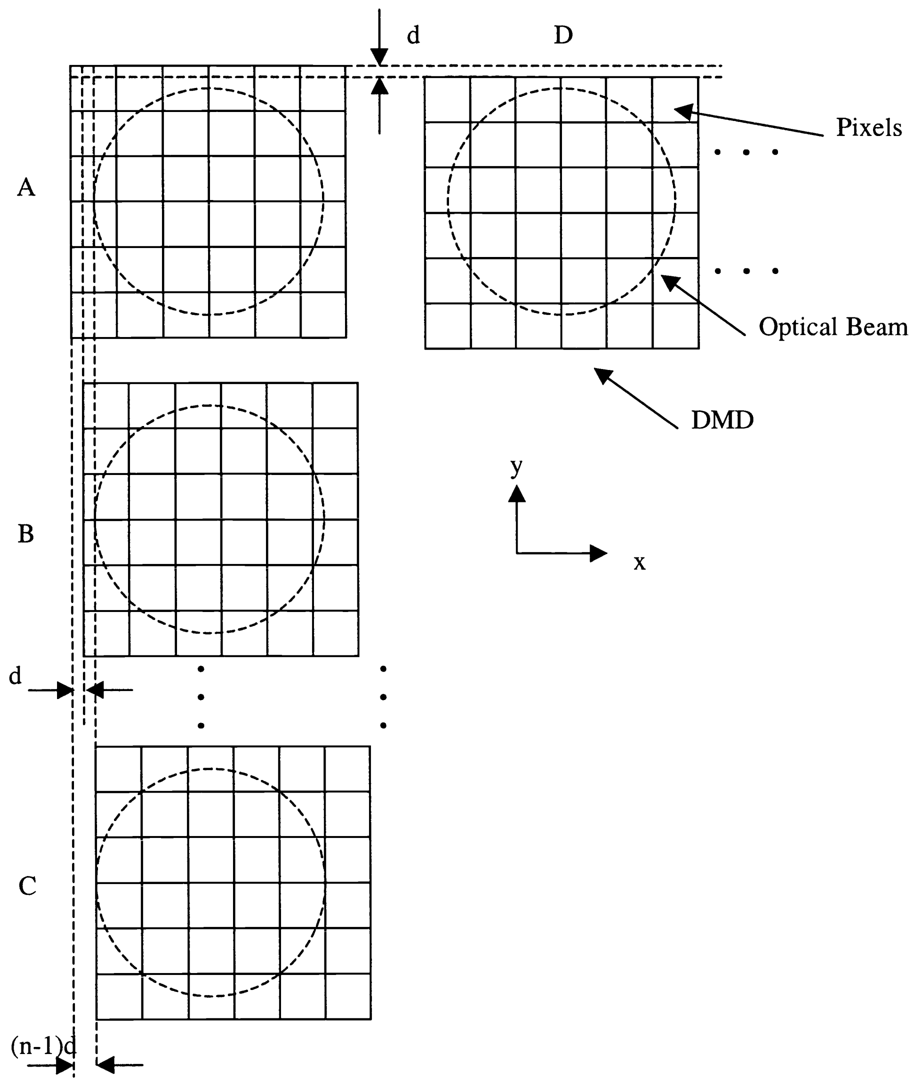


Fig.4 The basic implementation of the preferred embodiment of the digital-analog optical beam profiler using as a MEMS-based digital-analog motion controlled two-dimensional (2-D) small tilt micromirror device on a x-y fine translation stage. (A) to (C) show fine sub-pixel scale chip motion in x-direction while (D) shows chip motion in y-direction.

In Figure 4-A, we see a DMD chip with an optical beam under measurement at its center. By using these digital mode micromirrors, beam profile data can be measured, but the smallest data sample is limited by the pixel size. To take power measurements at sub-pixel level to lead to higher resolution beam profiles, the DMD chip is moved in its x-y plane and beam profile measurements are taken at each new x-y position. In Figure 4-B, the DMD is moved in the x-direction by a small distance d. Note that the beam remains at the original position. If the pixel/micromirror pitch in a DMD chip is divided into n sub-pixels, then the total chip displacement will be (n-1)d as shown in Figure 4-C. Since the DMD is pixelated with periodic pixels, it is only necessary to translate the chip a maximum one pixel pitch distance which typically corresponds to 13.8 microns for IR TI DMD. Hence, for TI chip, if n=10, then d=1.38 microns. In effect, a profile resolution of 1.38 microns can be obtained after signal processing.

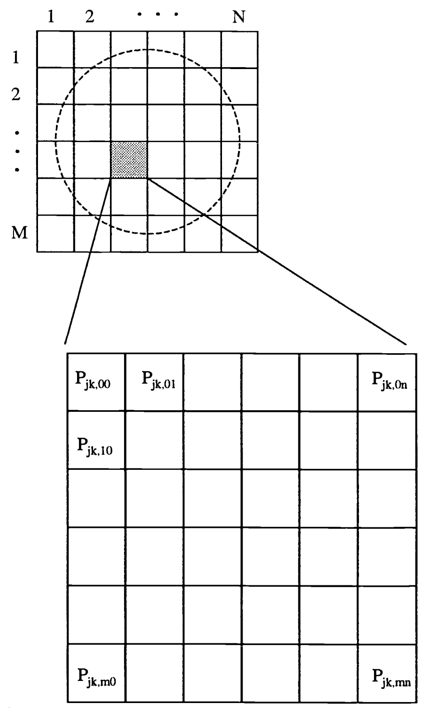


Fig.5 show sub-pixels are simulated via signal processing of data collected via the sub-pixel scale analog x-y motion of the 2-D DMD chip.

A similar procedure is repeated in the y-direction as shown in Figure 4-D. Once the data at all the chip positions has been obtained, then the power captured by sub-pixels (see Fig.5) can be calculated. In this method the digital nature of the DMD and its physical analog movement on a pixel pitch scale are used to increase the resolution of the measurements which was previously not obtainable. In effect, Fig.5 show sub-pixels are simulated via signal processing of data collected via the sub-pixel scale analog x-y motion of the 2-D DMD chip with MxN pixels.

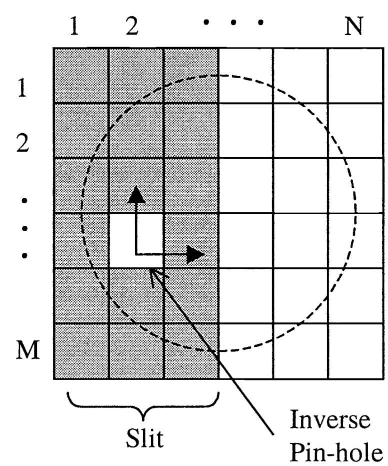


Fig.6 The working principles of another embodiment of the digital-analog beam profiler simulating the proposed slit-inverse pin-hole method that leads to high resolution profile maps.

Many beam profile measurement methods exist such as pinhole, knife edge and slit method. In this application we show how via the digital-analog beam profiler, the slit method can be combined with the pinhole method to give a new slit-inverse pinhole beam profiling method that can give highly accurate measurements with very little use of attenuators in the optical path. The procedure shown in Fig.6 is as follows: First a variable size slit is opened on the DMD such that enough optical power is captured by the detector to operate in its best operating region. Once this slit size is achieved, it is fixed for further measurements. The width of the slit will depend on incident power at the slit position. Once enough power is let through to the detector, the individual pixels or sub-pixels (explained in the previous section) will be switched to measure the light blocked by them (hence the name inverse pin-hole). Once the pinhole is scanned across this slit and power measurements are taken, the slit is translated in the orthogonal direction and the complete process is repeated beginning with slit size selection. The proposed slit-inverse pinhole method combines the best of both the slit and the pin-hole method. The slit method gives a control on the power which is let through to the detector, thus eliminating the need for an attenuator at the detector. The pin-hole method on the other hand gives power measurements at each position on the beam, thus making the measurement accurate and reducing the processing requirements as in multiple knife edge and slit methods, hence reducing the numerical error and the processing time.

5. INPUT POWER INDEPENDENT PROFILER DESIGN: AN EXTENSION

The earlier versions of the presented profiler as operated were sensitive to optical source power fluctuations that can lead to inaccurate spatial profile measurements. The purpose of the proposed section is to show how the digital optical beam profiler can be made insensitive to optical power fluctuations [3]. It is the object of this section to introduce an agile optical beam profiler using a two-dimensional (2-D) small tilt digital micromirror device/chip and single or pair photodetectors. This profiler features accurate optical beam profile measurements that are insensitive to optical power fluctuations of the light source under spatial measurement. The proposed embodiment involves digital control of the micromirrors on the 2-D micromirror array chip in time multiplexed conjunction with full face power measurements leading to a power referenced spatial measurement that is greatly insensitive to source power variations. Another embodiment of the profiler involves simultaneous use of two photodetectors for power measurement as the 2-D micromirror chip changes mirror settings to create mechanical moving objects such as slits or knife-edges used for spatial profiling. This method leads to optical source power insensitive spatial power maps of the beam profile. Any 2-D pixelated spatial light modulator device can be used to create the moving spatial samplers such as devices using liquid crystals, magneto-optics, multiple quantum wells, electro-optic polymers, and photonic crystals.

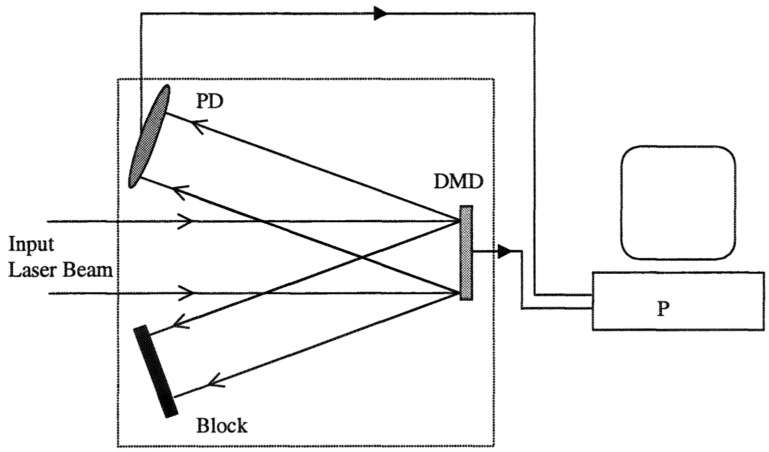


Figure 7: Proposed source power insensitive optical Beam Profiling Module using a single photo-detector (PD) for optical power measurements. PD: Photo Detector; DMD: Digital Micro-mirror Device; P : Processor/Data acquisition module/Computer etc.

Fig.7 shows the proposed invention that is a Beam Profiling Module using a single detector. Operation for source power insensitive beam profiling for this module is as follows (and also shown in Fig.8).

Step 1: Power from the slit k is directed to the photo detector PD.
Step 2: Power from the whole beam is directed to the photo detector PD.
Step 3: Power from the slit (k+1) is directed towards the photo detector PD.
Step 4: Power from the whole beam is directed towards the power meter.

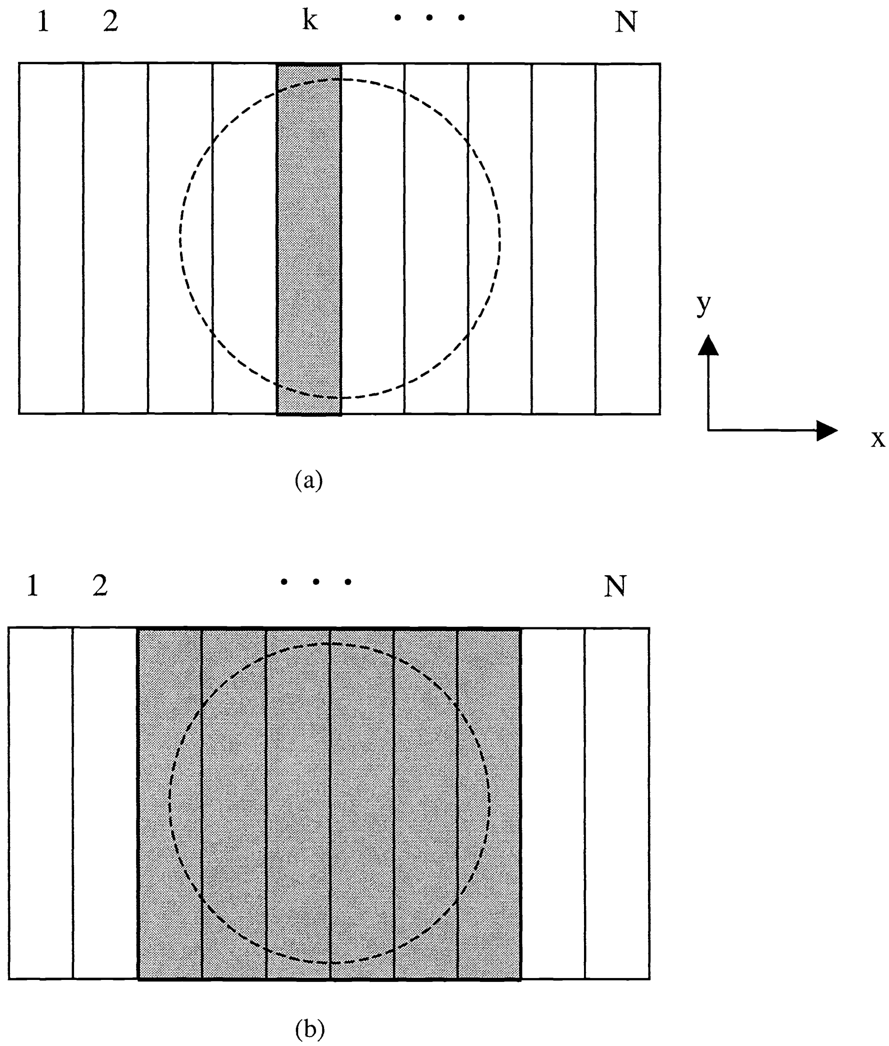


Figure 8. Time multiplexed DMD settings for the Fig.7 beam profiling technique using the single PD. (a) Power from the slit k is directed to the photo detector PD, and then (b) Power from the whole beam is directed to the photo detector PD. The order of (a) and (b) in time can also be reversed.

This process is repeated for all the slit measurements. In this way, the power measured from individual slits can be normalized by the total power and the temporal power variation can be canceled leading to a source power fluctuation and value insensitive accurate beam profiling.

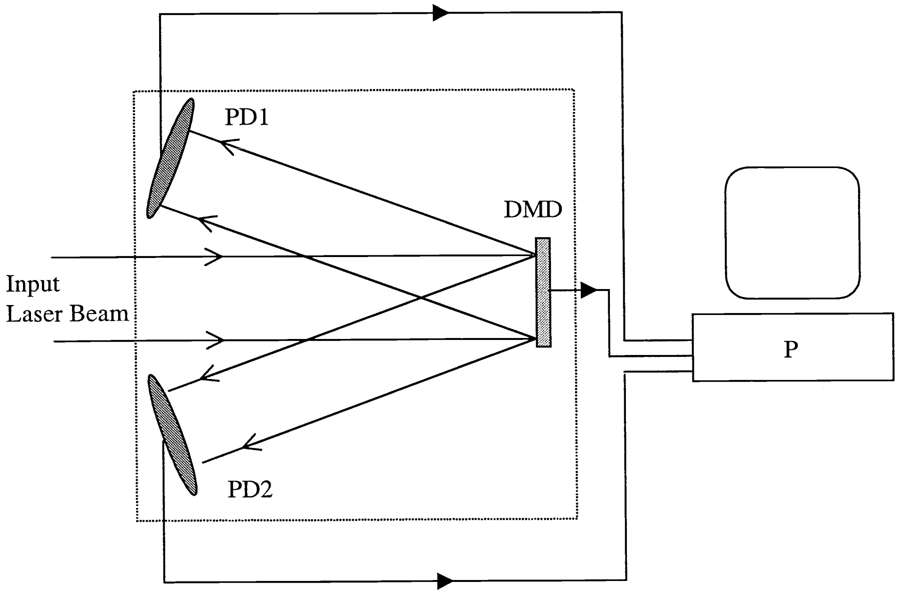


Figure 9. An alternate embodiment of the proposed source power insensitive Beam Profiling Module where compared to Fig.7, the proposed module in this figure uses two detectors, PD1 and PD2, to take simultaneous optical power readings.

Fig.9 shows an alternate embodiment of the proposed invention that is a Beam Profiling Module using two detectors, PD1 and PD2, for simultaneous power measurement. In this case, the profiler operation is as follows (and also shown in Fig.10).

As indicated in Fig.10, power from the slit k is directed to the photo detector PD1 and power from rest of the beam is directed to the photo detector PD2. Hence by this method we can normalize the measured power PD1 by dividing it by the sum of powers from PD1 and PD2. By using these two calibrated photo-detectors PD1 and PD2, the total power and the power from the slit can be measured simultaneously. Hence, the power fluctuations in the input beam can be canceled leading to source power level insensitive beam profiling. This is the case when PD1 and PD2 are calibrated detectors.

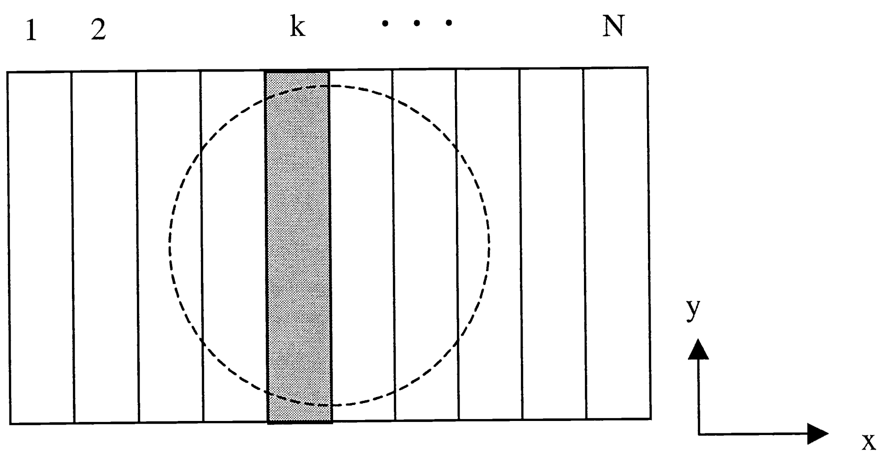


Figure 10. DMD settings for beam profiling technique in Fig.9 using two PD's. Power from the slit k is directed to the photo-detector PD1 and Power from the remaining beam is directed to the photo-detector PD2, allowing complete power referencing for power fluctuation insensitive beam profiling.

In the case that PD1 and PD2 are not calibrated, the Fig.9 and Fig.10 profiler method operates as follows with two photo-detectors operating simultaneously. Firstly, power from the slit k is directed to the photo-detector PD1 and then the slit is flipped to direct the total power of the beam to the photo detector PD2. In this way we can normalize the measured power PD1 by dividing it by power from PD2. By using two un-calibrated photo-detectors, the total power and the power from the slit can be measured simultaneously. Hence, the power fluctuations in the input beam can be canceled even through PD1 and PD2 are not calibrated. Compared to the Fig.7-8 single PD case where the PD can also be uncalibrated, the Fig.9-10 method using uncalibrated PDs gathers data faster as not a large amount of micromirrors have to be flipped per reading.

In general, Fig.7-10 introduce the power insensitive digital optical beam profiling concept using only slit measurements. It is important to note that other mechanical aperture measurements can also be used with the proposed Fig7. and Fig.9 systems such as pixel by pixel beam profiling, moving knife edge beam profiling, variable slit size beam profiling, variable aperture beam profiling, pinhole method, and inverse pinhole method.

6. CONCLUSIONS

The proposed DMD™ profiler technology has the attributes to meet the requirements to form the needed high power handling (5 kW/cm^2) broadband (visible, NIR, IR) spatial laser beam profiler for a maximum 10.5 mm diameter laser beam. In short, the NU-POWER™ beam profiler instrument with its various options ushers a new age of high repeatability, high reliability, fast, multiple mechanical beam profiling techniques within one cost-effective unit [3].

[1] N. A. Riza, US Patent No. 6,222,954, 2001.
[2] S. Sumriddetchkajorn and N. A. Riza, "MEMS-based digital optical beam profiler," Applied Optics, Vol.41, No.18, 20 June 2002.
[3] Patents pending.