All-digital and hybrid analog-digital beam profiling technology

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For the design and implementation of next generation super precision optical systems, the first commercially available hybrid analog-digital laser beam profiler is based on analog fine motion of a Digital Micro-Mirror Device (DMD) and within-chip digital control of near 1 million micro-mirrors acting as software programmable pin-holes. This wide area profiler provides sub-µm resolution with Watt level laser beams even at fluctuating power in the UV, visible, and near infrared. An equivalent all-digital LCD-based profiler is under development.

Technological state-of-the-art

Today, commercial direct high power laser beam profiling is done by conventional moving knife-edge methods that require super-accurate analog translation of a mechanical element over a long (e.g., cm) scale travel distance. Considering a typical 1 cm x 1 cm beam zone being devided into 10 000 x 10 000 bins of 1 µm resolution, the mechanical controls for such a mechanical profiler are severely challenged, leading to limitations in cost, reliability, and processing time as sampling area increases.

More complex profilers utilize the precise motion of multiple mechanical components such as multiple slits or pin-holes, adding to the complexity of the measurement system. In addition, imaging photodetector or two-dimensional (2D) charge coupled device (CCD) based profilers for direct profiling of high power laser beams are limited by detector saturation effects and inter-pixel charge crosstalk. Here, a 2D pixelated imaging device takes a direct time-integrated snapshot of the optical power 2D profile. Typically, these profilers are effective for low power (e.g., < mW) visible beam measurements.

Manufacturers have modified these visible and near infrared (NIR) light sensitive CCD profilers for IR applications by using IR sensitive phosphor films deposited over the CCD, thus producing indirect measurement of the IR beam. Such profilers suffer from spatial resolution limits due to charge diffusion in the phosphor films. In addition, the films have a non-linear output light response to the incident light, requiring constant device calibration and additional software processing, leading to a limited dynamic range for the profiler.

Thus, because of extensive use of moderate to high power laser beams in both research and commercial systems, there is a need to realize an optical beam profiler with high resolution, large beam characterization area, high reliability, laser power independent operation, high laser power handling, low cost, simple operation, and reasonably fast response.

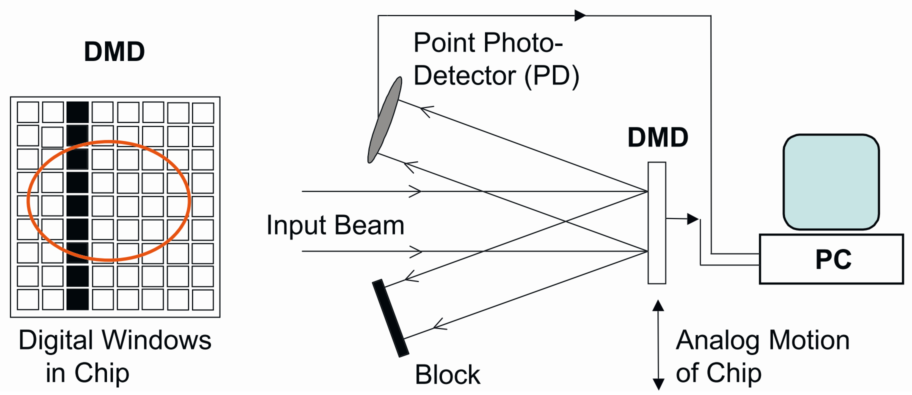

***Figure 1:** Principle of the beam sampling geometry based upon selectable chip pixels and setup (top view) of a beam profiler using a Digital Micro-Mirror Device (DMD) and one large area photo-detector (PD). For super-resolution hybrid analog-digital operation, the DMD chip is additionally translated in the lateral direction*

DMD–based beam profiler

Figure 1 shows the beam profiler innovation utilizing the Texas Instruments (TI) DMD chip and all-digital micro-mirror controls within the chip for coarse motion of the knife-edge-type aperture [1-4]. The light beam to be profiled is reflected from the DMD chip plane containing a two dimensional (2D) array of e.g. 786 432 small tilt digital micro-mirrors. Each micro-mirror has two states of operation, i.e., the $+\theta$ and $-\theta$ mirror positions. When the desired micro-mirrors are set to the $+\theta$ position, the corresponding part of the optical beam is reflected to the photo-detector and a power reading is taken. On the other hand when the specified micro-mirrors are set to

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the -θ position, the optical beam is directed to the absorber (or another detector if laser power independent operation is required). In effect, each micro-mirror acts like a photo-imager pixel; thus the micro-mirrors in the DMD collectively form a software controllable 2D array-based optical beam profiler. The spatial sampling resolution of such a digital-only mode optical beam profiler is limited by the pixel pitch of the DMD just like any pixelated CCD type profiler whose pitch generally ranges from 10–25 µm, depending on the specific device. Getting a device with a pitch close to 1 µm remains a challenge for both DMD and CCD designers.
Figure 2 shows the DMD chip configured for various profiling methods.

Hybrid analog-digital operation of the DMD–based beam profiler

The proposed figure 1 hybrid approach increases the resolution of the profiler beyond the pixel pitch limit. First, all-digital motion knife-edge beam profiling is performed by taking optical power measurements for different digitally-stepped knife-edge locations to produce an error-function profile with samples at intervals equal to the micro-mirror pitch of the DMD. For symmetric beams such as a Gaussian beam, differentiating the error function acquired from raw data gives the desired power distribution profile of the incident laser beam.
The profiling resolution limit imposed by the DMD pixel pitch is countered by subdividing the pixel pitch into '*n*' smaller equal steps, thus giving a new reduced spatial beam sampling step size. Hence the entire DMD chip is translated by this reduced step size and another all-digital knife-edge beam profiling operation is performed. This hybrid beam profiling procedure is performed '*n*' times by translating the DMD each time by the evaluated reduced step size. The '*n*' digital error-function profiles produced by the hybrid operations are normalized and re-arranged to a common spatial scale along the DMD translation axis, thus resulting in a final hybrid analog-digital error-function profile. This hybrid profile consists of '*n-1*' new samples within a pixel pitch, thus creating a super-resolution error function that has an '*n*' times higher spatial resolution than the DMD-based all-digital profiler.
For a 2D beam profile map, the DMD must be translated one pitch in both the x and y directions to acquire error function data for both directions. Note that because the DMD is translated a maximum one pixel pitch size, accurate analog motion control is required over a very small and manageable range. This makes the chip motion operations fast and repeatable and the overall beam profiling time is reduced considerably. Using sophisticated analog translation mechanics and motion controls, the resolution of the hybrid profiler can enter the nanometer regime.
For beam propagation characteristics, the DMD must also be translated along the optical axis (z direction).

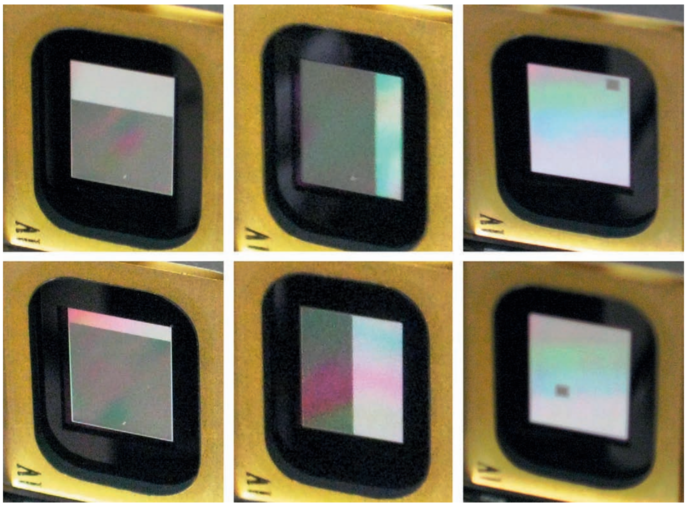

Figure 2: The DMD chip shown configured for various profiling methods: Y-moving knife-edge (left); X-moving knife-edge (middle); and pin-hole profiling on the X-Y coordinates chip grid (right)

Application example

The proposed hybrid profiler design shown in figure 1 has been implemented in the laboratory. Using a traditional coarse knife-edge profiler with a 10 µm step, the Gaussian 1/e^2 beam waist radius is measured to be ≈190 µm. Next, the digital-only mode of the DMD profiler is used to estimate this beam waist. The normalized error-function profile is obtained by performing this DMD-based digital-mode knife-edge experiment with 10 µm effective resolution, giving the **figure 3(a)** beam profile that provides a 1/e^2 beam waist radius of 187.3 µm.
For higher resolution via the hybrid mode, the fine analog translation is applied. The 10 µm pitch is divided by a factor n = 5; thus a 2 µm profiler sampling resolution is designed. Using a manually controlled precision mechanical stage, the DMD is translated five times by a distance of 2 µm in the direction of the moving digital knife-edge and the digital knife-edge experiment is performed. The five normalized error-function profiles obtained are shifted and plotted over a common axis, resulting in a final error-function profile with a spatial resolution of 2 µm that gives the **figure 3(b)** profile with a 1/e^2 beam waist radius of 188.4 µm. These beam waist results are consistent with each other and the mentioned classic knife-edge profiler measurement.
In addition, the profiler has also been tested with a laser beam whose power has been deliberately fluctuated in time. Initial experiments have been successfully performed in the all-digital mode for both high power (e.g., 1 W Ar-Ion CW Laser) visible and NIR wavelengths (e.g., 1550 nm centered band). **Figure 4** shows the typical profiler system set-up that includes a control PC, profiling software CD, the DMD, mounted on an alignment stage, and two photo-detectors connected to a power meter.

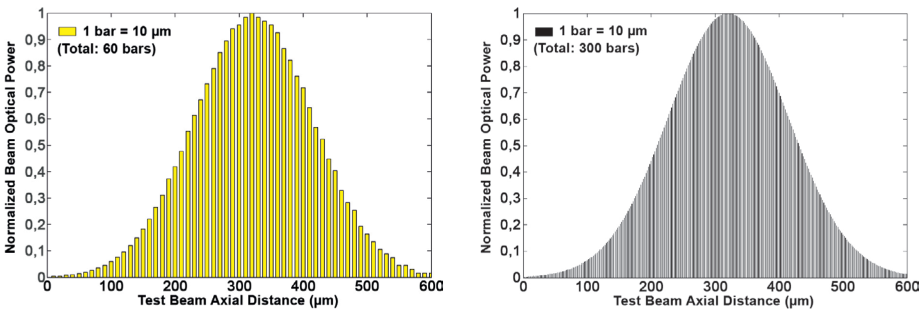

Figure 3: Gaussian beam profiles obtained from (a) 10 µm all-digital step and (b) 2 µm hybrid-step knife-edge DMD profiler experiments

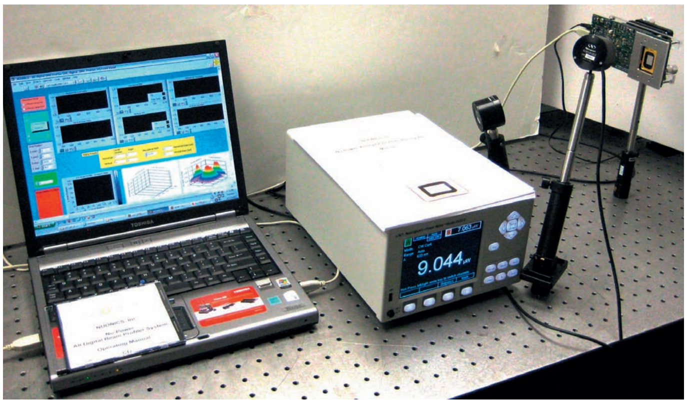

Figure 4: Typical DMD profiler system, showing the simplicity of the optical setup

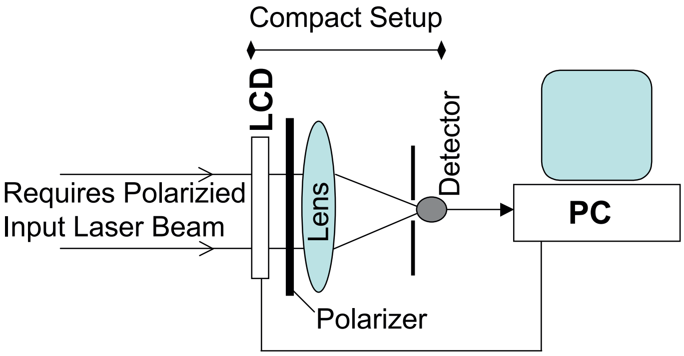

Figure 5: Setup (top view) of proposed compact all-digital beam profiler using an LCD chip and one large area photo-detector (PD)

All-digital LCD-based profiler

A new type of mechanical profiler under development for the first time takes advantage of the digital paradigm for profiling [5-8]. The word 'digital' does not simply imply the use of analog-to-digital (A-D) converters used on the electrical signal of an analog domain profiler such as a CCD or a mechanical profiler with analog power meter. Here, 'digital' refers to an intrinsically digital optical operation of the mechanical profiling process.

Figure 5 shows a corresponding more compact design of the proposed profiler using a transmissive liquid crystal display (LCD) instead of the moving micro-mirrors DMD. In this case, the software programmable LCD serves as an all-digital 2D no-moving parts chip that can generate the moving part element required for e.g. knife-edge or pin-hole measurements. Since the location of every LCD pixel is always the same over the incident beam cross-section, the software implemented moving pin-hole has the same exact positions as the measurement steps are repeated for reliable data acquistion. In effect, the all-digital nature of the LCD chip gives the proposed profiler its 100% measurement repeatability characteristics. Note that unlike the DMD-based profiler, the photo-detector in the LCD profiler can be placed right next to the chip if the lens is removed, thus realizing a transmissive super compact design with no moving parts, but at the expense of polarization dependency.

Conclusion

High-performance spatial beam measurements have a tremendous impact on the development of advanced laser and optical systems. But besides performance and reliability, cost is a key parameter for a wide spread use of beam profilers. The patented chip-scale design of the profilers presented above can lead to their cost-effective volume manufacturing. Particularly when nothing is known for certain about the optical beam under test, pin-hole profiling is the only answer. Nuonics is privileged to provide, to our knowledge, the only software controlled solution to this need.

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