Beam Profiler for Single-Photon Applications based on Compressive Sampling Techniques

Warren Grice[1*], Duncan Earl[1], Philip Evans[1], Dong-Sheng Guo[2], Travis Humble[3], Eric Martin[4], Raphael Pooser[1]

(1) Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
(2) Department of Physics, Southern University and A&M College, Baton Rouge, LA 70815, USA
(3) Computational Sciences and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
(4) Department of Physics & Astronomy, University of Tennessee, Knoxville, TN 37996
* gricew@ornl.gov

Abstract:
We report the development of a low-cost beam characterization technique appropriate for extremely low light levels. The technique makes use of compressive sampling strategies that have been developed recently for imaging applications.
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Introduction

Most quantum optics experiments require the control and manipulation of beams of light having extremely low intensities, often measured in units of photons per second. These low light levels make it difficult to carry out tasks that are almost trivial when applied to conventional laser beams. Although experimentalists have devised strategies through the years to meet this challenge, there remain a number of tasks that are still difficult at the few-photon level. One of the most important is beam characterization. For large photon numbers, this is typically accomplished by recording the beam profile directly using a multi-pixel device, such as a CCD camera. Unfortunately, most of these devices do not work well for low photon numbers and, despite the fact that several groups are working on photon-counting camera systems, this is not a viable approach in most laboratories. This is unfortunate because beam quality is important in many quantum optics applications, since poor beam quality can have an adverse effect on, for example, interference or single-mode coupling efficiency. Here we report the development of a low-cost beam characterization tool appropriate for extremely low light levels.

The technique makes use of compressive sampling strategies that have been developed recently for imaging applications [1-3]. When applied to beam profiling, compressive imaging offers higher photon flux and a reduced number of required measurements, both of which are advantageous for low-light applications such as quantum optics. However, there is reason to believe that the technique can be made even more efficient when applied to beam profiling. One reason is that, in many cases, a beam profile can be adequately characterized with just a few parameters, far less information than is needed for full image reconstruction. Another difference is that, in general, imaging by compressive sampling assumes no *a priori* information about the image. For beam profile measurements, it should be possible to devise an even more efficient measurement strategy that exploits certain assumptions about the beam, *e.g.* that it is approximately Gaussian.

The measurement apparatus is shown schematically in Fig. 1. The beam to be characterized is incident on a reconfigurable digital micromirror device (DMD), which subsequently directs it through collection optics and into a single photon-counting detector. The DMD comprises an array of tiny mirrors, each of which can be reoriented so as to direct the light either toward or away from the detector. With this arrangement, it is not difficult to imagine how the beam profile might be acquired. It is possible, for example, to activate one mirror at a time and record photocounts as a function of mirror location. However, this is a very time-consuming acquisition procedure, since each measurement captures only a tiny fraction of the available light, thus requiring lengthy integration times.

A compressive sampling approach offers two distinct advantages over the "pixel-by-pixel" technique. Rather than collecting photocounts arising from the light hitting a single mirror, a large number of mirrors throughout the array are activated for each measurement, with the pattern changing from one measurement to the next. The image in the plane of the DMD can be reconstructed using knowledge of the mirror patterns for each measurement, along with the corresponding photocounts. Because light from many parts of the beam contribute, this approach results in a substantially higher photon flux and a commensurate reduction in integration time. The second advantage comes in the number of measurements required. Whereas a conventional approach requires one measurement for each pixel, research in compressive imaging has demonstrated high quality image reconstruction with far fewer measurements.

To illustrate the viability of a compressive imaging approach to beam profiling, we measured a complex beam profile generated from a collimated fiber optic laser source. An image of the beam profile was first acquired using individually scanned pixel measurements over a 32 pixel x 32 pixel area of a DMD. The scanned image is shown in Fig. 2(a). Subsequently, the same beam profile was "sampled" using approximately 1000 patterns generated from a

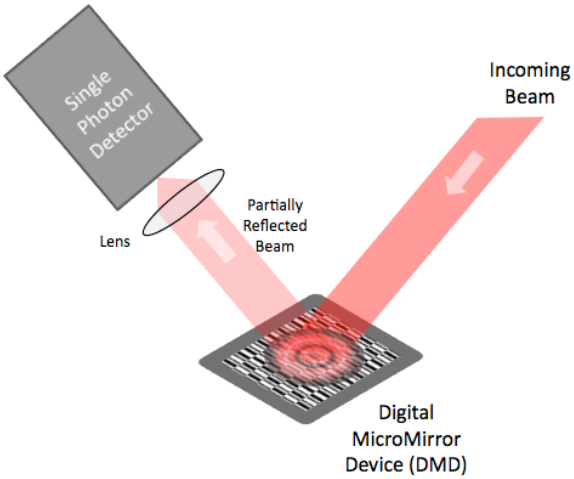

Fig. 1. Measurement apparatus. Light from the beam to be characterized is reflected from the DMD into the detector.

32 x 32 element Hadamard sensing matrix. The "sampled" data was then used with an algorithm (SEDUMI) that minimizes the L1-norm to reconstruct the beam profile image. The image in Fig. 2(b) shows the reconstructed image - which closely agrees with the scanned image. The detector gain required to generated the scanned image was approximately ten times greater than the gain required to generate the compressive image, demonstrating one of the key advantages of the compressive imaging technique.

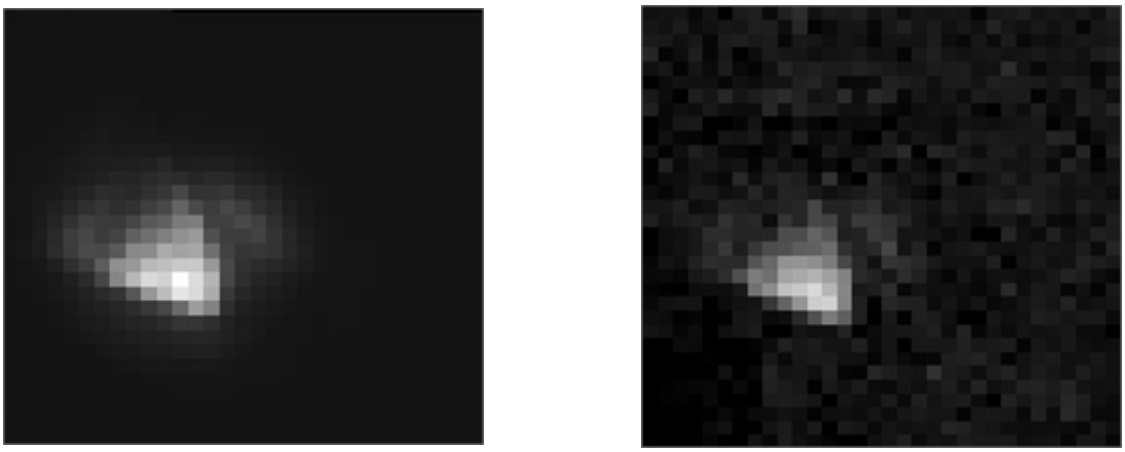

Figure 2: Results from a beam profiling measurement. The profile shown in (a) was acquired using a pixel-by-pixel scanning method. The profile shown in (b) was acquired through a compressive sampling method.

References

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