The design and characterization of the laser beams used in NPLI’s Cesium Fountain experiment is described in the present paper. A 1-D photodiode array based instrument was indigenously developed for this dedicated purpose. Major advantages over the conventional 2-D array based instruments include stand alone operation, reduced cost and computational requirements. This instrument specifically finds applications for direct measurement and analysis of broad laser beams (FWHM~20 mm).

Keywords: Laser beam measurement, Instrumentation, Microcontrollers, Cesium fountain clock

1 Introduction

The Time & Frequency Division of the National Physical Laboratory India (NPLI) is presently developing a Cesium Atomic Fountain Clock. One of the many modules of this interdisciplinary project requires laser cooling of Cesium atoms using coherent IR laser beams of 852 nm wavelength. These are expanded beams with a full width at half maximum (FWHM) of about 10-20 mm. Before expansion, laser beams are transported (from the optics table to the physics package) via polarization maintaining single mode optical fibers. The light coming out of a fiber tip is a thin diverging beam. This is expanded with the help of a beam expander assembly. The schematic of a beam expander indigenously developed for NPLI fountain is shown in Fig. 1. The light coming out of the fiber passes through a polarizing beam splitter (PBS) which acts as a polarizer. The linearly polarized light then passes through a correctly oriented λ/4 plate which turns the polarization to circular polarization. Circularly polarized beams are required for laser cooling and trapping of atoms in a magneto-optical trap (MOT).

In order to collimate the expanded beam, a plano-convex lens is placed at a distance (equal to the focal length of the lens) from the tip of the fiber. Precise adjustment of the distance of the lens from the fiber tip can be done with our special design of two threaded coaxial tubes (as shown in Fig. 1) which can slide over one another. Expanded beams coming out of the beam expanders need proper characterization in terms of collimation, center of gravity and spatial intensity variation. These properties of the laser beams are of paramount significance for the laser cooling experiment and hence the need for a beam profiler.

Laser beam profilers are electronic instruments that are capable of capturing, displaying and recording the spatial intensity profile of laser beams. These instruments help us to obtain a visual representation of a beam and thus find extensive applications in high precision optics related research. Sophisticated beam profiler equipments are commercially available and capable of producing highly detailed profiles. However, some aspects unique to the experimental set-up demand several performance factors other than precision alone. These include portability, certain lower limit of frame grabbing rate for dynamic measurements, the capability to operate independent of PC support and the ability to provide direct measurement for laser beams with large diameter (FWHM~20 cm). Using a 1-D photodiode array in place of a conventional 2-D array for capturing the spatial intensity profile of a laser beam yields a 2-D
profile instead of a more descriptive 3-D profile; nonetheless it also reduces the cost and computational requirements substantially. The above factors influenced our decision to develop such an instrument customized for the needs of the main experiment.  

2 Design of the Instrument

2.1 Sensor element

A 1-D array of photodiodes was chosen instead of a conventional 2-D CCD based sensor arrays popularly used in imaging equipment. Among the various available alternatives in this category of sensors, we have employed the A5V-35 array. It features 35 single element photodiodes laid adjacent to each other with a known pitch of 0.99 mm. The known mutual separation (pitch) between the array elements helps in spatially relating the various detected intensities. Thus, a ‘slice’ of the waveform of the beam is obtained. The sensor is housed inside a metal case alike the base unit as shown in Fig. 2(a, b and c), respectively. A signal conditioning circuitry accompanying the sensor array is also housed within the sensor unit casing and it provides current to voltage conversion with sufficient gain to the raw photodiode outputs (typically few µA) so that they do not become contaminated by noise when interfaced with the acquisition cum processing base unit situated at long distance. This circuitry draws its operational power from the base unit and so far, we have observed satisfactory performance while they are connected by a nearly 2.5 m cable.

2.2 Acquisition and Processing Unit

The schematic in Fig. 3 shows the general working of the hardware and how data is acquired by the processor of the instrument through analog multiplexing and subsequent analog to digital conversion (12 bit resolution, successive approximation) of the voltages obtained above. The analog-to-digital converter (AD574A, 12-bit, successive approximation), processor (ATmega16 microcontroller), LCD read-out module along with the serial port interface are encased within the base unit shown in Fig. 2(b). The acquired data is transmitted to the PC via a serial-to-USB cable. The serial interface protocol used is RS-232 at 9600 baud rate. The complete unit requires about 90 mA of current and a bipolar ±12 VDC supply. An on board step-down transformer and AC-DC converter allows this system to be directly plugged in to any 220 VAC, 50 Hz domestic power outlet. Additional description of the aforementioned signal conditioning circuitry as well as acquisition and processing are provided in Ref. (4).

2.3 Read out

A dual line LCD module is used to display the necessary information [Fig. 2(b)]. Additionally, a 2-D plot of the spatial intensity profile is produced on a customized PC software.

![Fig. 2 — Our laser beam profiler system with (a) the sensor array, (b) base (acquisition and processing) unit and (c) the complete system, wired together enabling remote acquisition from a distance of typically 8 m](image)
3 Features and Operation

The beam profiler system features provision for measuring the following parameters.

3.1 Central maxima

The sensor array comprises of an odd number of sensors (35 elements) and the central element (18th element) is assumed to be the origin due to symmetry. Accordingly, each photodiode element is given an index within the range of -17 to +17 (both inclusive). While measuring, the index of the photodiode element receiving the maximum optical power is displayed on the LCD module. This process involves dynamic tracking and the system can deliver a frame grab frequency of up to 20 Hz.

3.2 Deviation from ideal behavior

The general equation that describes a three dimensional Gaussian distribution is given by Eq. (1). Practically, the IR laser beams are found to be slightly elliptical owing to the geometry of the typical laser diodes. However, due to typically low eccentricity values of the elliptical cross-section, we assume them to approximately follow a circular Gaussian distribution, where \( \sigma_x \approx \sigma_y \).

\[
f(x, y) = Ae^{-\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma_x^2} - \frac{(x-x_0)^2 - (y-y_0)^2}{2\sigma_y^2}}
\]  

...(1)

The actual profile of the beams, however, may exhibit certain deviations from the ideal behaviour. A glimpse of the profile itself can give us a rough estimate of this deviation, revealing jitters or other non-uniformities, but the absence of PC support leads us to seek an alternative method. A simplistic parameter to measure this deviation can be the r.m.s error which can be defined as follows:

\[
e^2 = \frac{1}{i \times j} \left\{ \sum_{i} \sum_{j} f_{ob} (x_i, y_j) - f_{id} (x_i, y_j) \right\}^2
\]  

...(2)

where \( f_{ob} \) and \( f_{id} \) represent the observed and ideal spatial (optical) intensity distribution, respectively, in terms of the voltage read-out from the sensor array. The parameters ‘i’ and ‘j’ are used to index the active sensor elements in the array. Thus, by displaying the value of the above error parameter on an LCD module, we can obtain an approximate idea about the beam quality. An abnormally high value might be attributed to the sensor plane not being perpendicular to the principal axis. This reading can thus assist in alignment procedures along with the offset reading.

3.3 FWHM

Among the many definitions of the diameter of a laser beam, we adopt the FWHM or full width at half maximum. In two dimensions, the general expression given in Eq. (1) reduces to Eq. (3) described below.

\[
f(x) = ae^{-\frac{(x-b)^2}{2\sigma^2}}
\]  

...(3)

Substituting \( f(x) = a/2 \) and solving for the roots of \( x \) immediately leads to Eq. (4) below:

\[
FWHM = |x_1 - x_2| = 2\sigma \times \sqrt{2\ln(2)} = 2.354\times \sigma
\]  

...(4)

The value of FWHM can be calculated experimentally by the processor used in the profiler instrument and it can be used for the following two purposes:

Display — This value may be displayed on an LCD to provide a fair idea about the beam width. This can further be used to conveniently check collimation of the beam by measuring the FWHM value at different distances from the beam source.

Calculation — The value of ‘\( \sigma \)’ can be calculated and used iteratively to develop a plot of the profile with finer precision. This is used in the accompanying PC suite discussed later. Before the FWHM calculations are carried out, the 35 sample points of the intensity profile captured as voltage levels by the sensor array are algorithmically interpolated to 3500 points. Since the arrays are spatially separated by 0.99 mm, the calculated FWHM has a resolution of \(~0.01\) mm.

4 Characterization Methodologics

4.1 Angular alignment

The mechanical construction of the fiber holder and the beam expander ensure the positional alignment of the tip of the fiber. However, it does not guarantee angular alignment of the principal axis of the fiber with the principal axis of the remaining optics. Thus, in spite of precise adjustment of the co-axial threaded tube so as to produce a collimated beam, it may not be parallel to the principal axis of the rest of the optics as shown in Fig. 4. Though infrequent, there remains this possibility of procuring a non-zero angle between the two principal axes during initial installation and therefore, should be examined.

The above examination is carried out in two different stages. In the first stage we try to visually determine the beam’s center of gravity. For this, we
image the emergent beam on a translucent screen pre-demarcated with contours and cross hairs as shown in Fig. 5. The center of this screen is made to align with that of the circular aperture of the beam expander and the image formed is captured by an IR sensitive CCD based camera. Such images obtained for all our beams indicated good alignment; however, a second analysis was performed to quantitatively verify the alignment as well as the Gaussian nature of the beam.

To perform the second analysis, we placed the sensor array of our beam profiler system at relatively large distances (~25 cm), letting the angular deviation (if any) produce a noticeable effect. The center of the sensor array is made to coincide with the principal axis of the optics. Since our sensor is essentially one dimensional in nature, two ‘length on’ readings are required with the orientation of the sensor array altered by 90°. The set-up is described in Fig. 4, depicting only one of the two orientations. A severe angular misalignment would result in a large value of the beam offset reading, r.m.s error reading as well as a skewed plot of the profile of the beam. To observe a degraded plot of the beam profile (to an exaggerated extent) we deliberately misaligned the principal axes of the optics and the sensor array by an arbitrary 5°. The resulting plot obtained in the PC software developed to complement the beam profiler hardware, is shown in Fig. 6. Our beams were found to contain no such major misalignment issues.

4.2 Collimation analysis

Examination of collimation of the beams was carried out by a set of very basic experiments. The set-up for it is essentially the same as shown in Fig. 4. For each beam, two sets of profiles were recorded with our beam profiler system. In addition to displaying the profile plot, the software accompanying the system also displays the calculated FWHM (experimental and ideal) and r.m.s. error values on a separate section of the screen, shown in Fig. 7. These values were also recorded for each of the two different sets. For the first set, the sensor array was positioned at a short distance (~2 cm) from the beam expander and for the second set, the sensor was placed at a longer distance (~25 cm). The sensor
is not placed away any further since the maximum required length of the beams is not to exceed 20 cm. Thus, reasonably close values of the FWHMs obtained in the two different sets would conclusively confirm the collimation of the beams for all our practical purposes.

Our nomenclature for the beams used is shown in Fig. 8. The experimentally recorded average FWHM values of these eight laser beams used are provided in Table 1.

4.3 Three dimensional imaging

As a final analysis, a complete three dimensional profile of each beam was obtained by superimposing a number of such two dimensional profiles as shown in Fig. 6; translated by a known distance. The translation is done in a direction mutually orthogonal to the length of the sensor array and the principal axis of the beam. Applications employing similar methodology for obtaining complete 2-D image profiles by mechanically scanning a 1-D array can be found decades ago. In more recent times, in spite of the availability of affordable 2-D sensor arrays, the simplicity of this method still appeals to the research community when it comes to direct, lens-less imaging of radiation patterns larger than few centimeters. In fact, this is fundamentally the same method used by photocopying machines, flat-bed scanners, fax machines, etc.

In this case, the sensor array is set-up in a fashion similar to Fig. 2(a), facing the beam expander. A different stand is used with the help of which, the vertical position of the sensor module can be translated by a known distance (1 mm). Starting from well below the beam, the sensor is moved in discrete lengths (1 mm) and made to image the profile of the beam for each such instance. The resulting plot data are saved and later combined to yield a composite approximation of the three dimensional spatial intensity profile of the concerned beam. This is very useful for visually confirming the overall symmetry of the beams. One such plot is shown in Fig. 9, for the D1 laser beam. The same data is imaged on the horizontal plane and shown in Fig. 10. This gives another visualization of the cross-section of the beam.

If the FWHM is measured along the two perpendicular lines passing through the center of the plotas, it is revealed that the cross-section is slightly elliptical, with the horizontal FWHM slightly longer.

It should be noted here that while there is a standalone dynamic tracking mode of operation that delivers up to 20 Hz of frame grabbing frequency, in the PC interface mode, each measurement takes nearly 250 ms. This delay can be attributed to the time taken for the serial data transmission from the acquisition module [Fig. 2(b)] to the PC to be
completed as well as the interpolation and curve fitting algorithms performed by the software before displaying the results. In addition to this, the sensor module is moved manually at present which takes additional time before it can be adjusted to a new height for the next reading. Using motorized optomechanical components can solve the latter problem but the maximum attainable frame would be limited by the software delay to about 4 Hz. In this respect, commercially available CCD based beam profilers, such as the LBP-x-USB (x=1-4) by Newport and BC106-VIS-CCD Camera Beam Profiler by Thorlabs can typically deliver 25 Hz and 43 Hz of frame-rate, respectively in their minimum resolution of operation, making them a more viable option for real-time applications.

5 Conclusions

In the present paper, a brief discussion is presented on the characterization methodology of expanded laser beams that are being used for the cesium fountain experiment at NPLI. Application of some of the systems indigenously developed for this experiment, such as the beam expanders and the laser beam profiler package, was highlighted. In spite of high precision beam profilers being readily available, their limited sensor area (in general) would have required the use of intermediate optics for analyzing beams of the expected dimensions in our experiments. These commercially available beam profilers tend to highlight features such as high spatial resolution (inter-pixel distance <10 µm), high power sensitivity range (<1 nW), high damage threshold (~10 W), real-time video capture mode etc. Large number of sensor elements (640x480, 1360x1024 etc.) contained in 2-D sensor arrays employed by these beam profilers increase the field-of-view but require computational power that is beyond the capabilities of contemporary on-board embedded processors. Hence, these are often devoid of any PC independent analysis means but are accompanied with feature laden software suites, often capable of performing advanced mathematical operations such as multi-dimensional FFT, convolution etc. While such specifications are certainly favorable for applications demanding high-precision; requirements unique to the main experiment of NPLI’s Cesium Fountain Clock were not addressed that mainly included PC independent portable operation and lens-less imaging of I.R. beams of diameters up to 20 cm (FWHM). In these respect, the thrust features of the commercial profilers thus appear to be cost inflating redundancies. The laser beam profiler presented in this paper was built with a “ground-up” approach with these specific needs in mind and it addressed our requirements in a more than satisfactory fashion. The cost of construction of this first prototype was nearly $500, with the photodiode array itself accounting for 80% of the cost-and this stands at a fraction of commercial profilers such as the LBP-4-USB (Newport, presently listed at ~$4500) and BC106-VIS-CCD (Thorlabs, ~$4000). Hence, for our specific application, the system presented itself as a highly cost-effective solution and we sincerely believe that many such unique requirements akin to the ones described in this paper exists in the scientific community and that the methods described in this paper will appeal to them.

References

5. ASV-35 datasheet, OSI Optoelectronics.