

# Laser beam spatial profile analysis using a two-dimensional photodiode array

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A system for the spatial characterization of a laser beam using an optoelectronic imaging device is described. A two-dimensional photodiode array interfaced to a small computer is used to obtain the image of the beam's cross section; the peak position, peak intensity, and Gaussian peak width can then be computed and displayed. Details of the array interface, the graphics, and the data-processing algorithm are provided.

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## INTRODUCTION

The spatial characteristics of a laser beam in the plane perpendicular to the direction of propagation are important parameters for a wide variety of laser experiments. Knowledge of the  $1/e^2$  radius at different distances from the output mirror is necessary to find the beam's divergence. Accurate measurement of the beam's radius as it passes through a lens (along with the beam's divergence) is necessary to calculate the focused beam's radius. In the confocal region the beam radius is necessary to calculate an intensity, or to predict other optical effects such as those experienced in correlation spectroscopy.<sup>1</sup> Typically the spatial profile is Gaussian.<sup>2</sup> In lasers using Brewster angle optics the limiting apertures in the vertical and horizontal planes may differ slightly, generating a Gaussian profile with different Gaussian radii in the vertical and horizontal planes.

An alternative to the conventional methods of determining the beam profile is the use of an imaging device capable of providing an image of the beam cross section in near real time. Electronic imaging devices created for the video imaging industry have appropriate optical, electrical, and geometric characteristics. Each is composed of a two-dimensional array of detector elements called pixels (*picture elements*) which independently respond to visible light and are normally accessed serially by the readout electronics. Several have been used successfully by spectroscopists, primarily placing wavelength on an image axis. These devices include photodiodes,<sup>3</sup> vidicon tubes,<sup>4</sup> charge-coupled devices,<sup>5</sup> and charge-injection devices,<sup>6</sup> although many other devices have been tested with lesser success.<sup>7</sup>

All of these devices have good sensitivity in the visible and near-IR regions and are available in two-dimensional formats. An appropriate device for the task of imaging a beam is one whose cross section is comparable to that of the beam in order to avoid aliasing the image or introducing distortion from the convolution of the image with the aperture of a single pixel. Typically, values for  $1/e^2$  laser beam radius range from 0.5 to 1.0 mm. Ninety-nine percent of the energy will pass through an aperture of diameter equal to three times this radius.

## I. THE DETECTOR ARRAY

The Reticon RA-32 $\times$ 32A photodiode array includes a 32 $\times$ 32 matrix of photodiode elements with 100- $\mu$ m pixel spacing; each pixel measures 70  $\mu$ m. Therefore, a beam of 1.0-mm  $1/e^2$  radius can be completely intercepted. It is nearly ideal for this application.<sup>8</sup> For larger beams, a similar but larger array, Reticon RA-50 $\times$ 50A is available. In these studies we used the smaller array which provided the necessary aperture and resolution to characterize a TEM<sub>00</sub> Nd:YAG laser.

The array is an integrating device; each pixel contains an integral capacitor which holds the charge due to the light intensity integrated over the exposure time until it is accessed by the readout electronics. The signal due to a laser flash is stored on this capacitor until it is read. The various waveforms and amplifiers required to drive the array are provided by a demonstration circuit board, Reticon RC-100B.

A cooled array can be used to integrate exposure for up to several seconds, limited by the thermally generated dark signal. The information must be read from the photodiode array at high clock rates; charging the capacitance on each pixel at low rates introduces some nonlinearity. A clock rate of 100 kHz is suitable.

## II. THE COMPUTER SYSTEM

A block diagram of the PDP 11/03 computer with a 100-kHz analog front end and graphics output used for data acquisition and processing is shown in the bottom portion of Fig. 1. A Data Translation 1761 analog-to-digital converter (ADC) subsystem is operated in the direct memory access (DMA) mode. Other subsystems include a programmable real-time clock (DEC KWV-11) and a quad digital-to-analog board (ADAC 600-LSI-11D).

The computer is operated under the RT-11 operating system with 56-kbyte memory, dual flexible disk drives (DEC RX01), and a 40-Mbyte "Winchester" disk (Kennedy 5300). A vector-type graphics system is produced on an x-y oscilloscope driven by a pair of DAC's. A Tektronix 4006

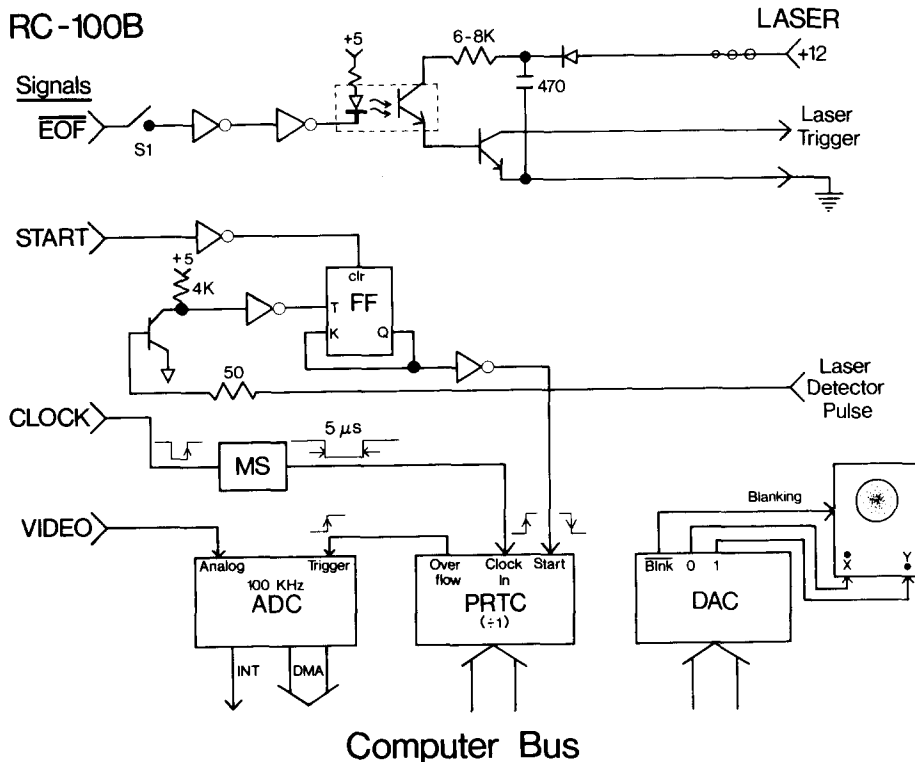


FIG. 1. Interface between the RC-100 B demonstration board for the photodiode array and the computer peripherals. FF = flip-flop; MS = monostable; resistances are in Ohms and capacitances in microfarads. Other abbreviations are described in the text.

terminal is used for displaying the data and a Tektronix 4662 plotter produces the hard copy.

### III. THE INTERFACE

In a sense, the computer acts as a storage oscilloscope, acquiring and storing the data. However, in contrast to the oscilloscope, the photodiode array measurement system must trigger the experiment rather than vice versa for the following reasons: First, the photodiode array must be read out at regular intervals since the dark signal builds up rapidly when the clock is stopped. Second, the exposure period for a given pixel begins when it is read out. Consequently, it is essential that the laser flash be timed to occur at the end of a frame readout, that is, between the readout of the last line of one frame and the first line of the next. Therefore, the laser must be triggered by the array's clock, and the data acquisition begins with the start of the first line.

The required timing diagram is shown in Fig. 2. After the laser power supply has charged, switch S1 is manually closed, and the laser is subsequently triggered when the following end-of-frame (EOF) pulse goes LO. Although the laser introduces a variable delay between the trigger and the laser pulse (300 to 400  $\mu$ s), the pulse will normally occur before the START pulse which indicates the start of the readout of the next line. The falling edge of the PRTC STRT pulse is used by the programmable real-time clock (PRTC) to turn on the clock pulses from the array board which trigger the ADC; PRTC STRT is set HI by the photodiode pulse indicating a laser pulse so that its falling edge is produced by the leading edge of the first START pulse.

The interface circuit required to implement the timing diagram is shown in the top portion of Fig. 1. The (EOF)

signal from the array board triggers the laser by grounding the trigger input. An optical isolator, internally composed of light-emitting diode (LED) D1 and phototransistor Q1, is used to electrically isolate the laser from the computer system; the isolator drives a transistor (Q2) in a Darlington configuration powered by the unregulated 12-V laser power supply.

Shown in the bottom portion of Fig. 1, a fast photodiode detects a portion of the laser pulse, and that signal is shifted to a TTL level by transistor Q3, arming the flip-flop. The

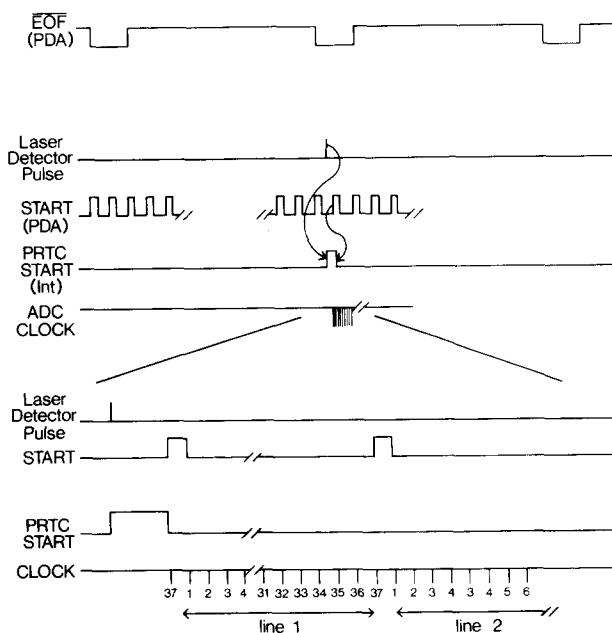


FIG. 2. Timing diagram showing the relationships of signals used in the interface.

START pulse from the array board can then trigger PRTC STRT which opens the gate in the programmable real-time clock board sending pulses to the ADC. A short delay ( $5\ \mu\text{s}$ ) is generated in the CLOCK signal with a monostable in order to allow the signal for each separate pixel to settle before the ADC is triggered. Each of the 32 lines from the diode array contains 37 diode outputs. Under software control, signals from the least five pixels of each line and the entire last line which contain no information are removed. In the control program, the first pixel of each line was deleted because its saturation voltage is different from that of the remainder of the pixels.

#### IV. THE SOFTWARE

The main routine was prepared in FORTRAN with drivers for the interface written in assembly language. The software modules to be described include the driver routine for the interface, the vector graphics driver, a plotting routine, and the data-processing software.

The interface driver sets up the PRTC and the ADC subsystems. The PRTC is set up as a modulo-one divider; the initialization arms the divider to be turned on by the Schmitt trigger input. The DMA function of the ADC subsystem is then enabled after loading both the address of the memory block into which the data array is to be stored and the number of data (1024) to be acquired. For the DMA function to be able to operate at a maximum rate, the possibility of conflict with the processor is removed by halting the processor. When the acquisition of 1024 data is complete, the ADC subsystem generates an interrupt which restarts the processor. The clock input to the ADC is then halted.

A nearly instantaneous visual representation of the data is necessary for the operator in order to get a rough idea of the position of the laser beam and to determine if either a particularly intense pulse saturated the detector or the pulse is insufficiently intense, making characterization difficult.

Display of the data plotted as a surface on the CRT terminal requires 2–3 min. Therefore, several methods of display on an oscilloscope were investigated; the one which was by far the easiest to interpret will be described.

Using a pair of DAC's connected to the  $x$ - $y$  inputs of an oscilloscope, the beam is rastered across the screen, moving to each position in a  $32 \times 32$  matrix. A separate control bit of the DAC subsystem is connected to the BLANKING input of the oscilloscope; when that pulse is LO, the beam is blanked. A low threshold, about 10% of full scale, is set, and only when the datum corresponding to the  $x$ - $y$  position exceeds that threshold is the BLANKING input disabled. After a scan of all points, the threshold is increased, and the process is repeated until the saturation level is reached; then the threshold is reset to 10% and the process is repeated. By repeatedly following this sequence, the dynamic image of a large spot decreasing to a point is displayed.

A keystroke during the data display allows the operator to choose whether to display the data on the graphics CRT, to plot it on the plotter, to process the data, or to store it on the disk. The plotting software was written using modified PLOT-10 software (Tektronix), and a typical plot of data (after background subtraction) is shown in Fig. 3.

#### V. DATA PROCESSING

Once the data have been accumulated and visually inspected, it is processed to obtain the position parameters. These parameters can be obtained by several techniques. One method uses the sum of the intensities over the array to find the power, a "center of gravity" calculation to determine the center, and an iterative procedure to find the diameter.<sup>8</sup> However, since the beam has a known shape, a fit of that model to the data is preferable. The concept is quite uncomplicated: a two-dimensional Gaussian peak is fit to

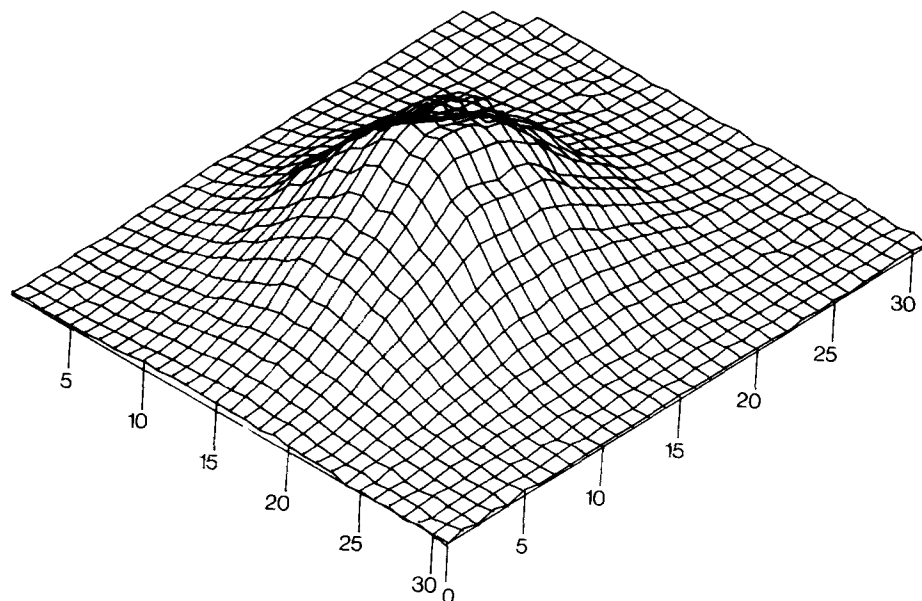


FIG. 3. Spatial profile of a single picosecond pulse as measured with the photodiode array system.

the data by the method of least squares. However, the implementation on a small computer is not without its pitfalls; consequently, an outline of the procedure is in order.

The peak has a maximum at location  $p_x, p_y$  where the amplitude is  $A$ . The fit is allowed to have separate widths  $w_x$  and  $w_y$ , in the  $x$  and  $y$  dimensions, respectively, where  $w_x, w_y$  are the  $1/e$  radii. The resultant model equation for the intensity  $Z_{xy}$  at any point is, therefore,

$$Z_{xy} = A \exp\left(\frac{-(x - p_x)^2}{w_x^2}\right) \exp\left(\frac{-(y - p_y)^2}{w_y^2}\right).$$

The linearization requires taking the log of both sides so that

$$\ln Z_{xy} = \ln A - \frac{(x - p_x)^2}{w_x^2} - \frac{(y - p_y)^2}{w_y^2},$$

which can be rearranged to form

$$\ln Z_{xy} = \ln A - \frac{p_x^2}{w_x^2} + 2\left(\frac{p_x}{w_x^2}\right)x - \left(\frac{1}{w_x^2}\right)x^2 - \frac{p_y^2}{w_y^2} + 2\left(\frac{p_y}{w_y^2}\right)y - \left(\frac{1}{w_y^2}\right)y^2.$$

This equation takes the form

$$R = b_0 + b_1 x + b_2 x^2 + b_3 y + b_4 y^2,$$

which can be solved for estimates of the values of  $b$  by using the least-squares equation

$$\mathbf{B} = (\mathbf{F}'\mathbf{W}\mathbf{F})^{-1}\mathbf{F}'\mathbf{W}\mathbf{R},$$

where  $\mathbf{B}$  contains the estimates of  $b$ ,  $\mathbf{F}$  contains the values of  $x, x^2, y$ , and  $y^2$ ,  $\mathbf{F}'$  is the transform of  $\mathbf{F}$ ,  $\mathbf{W}$  contains the weights, and  $\mathbf{R}$  is the matrix of values  $\ln Z_{xy}$ .

An estimate of the weights is essential to the proper calculation of the coefficients and is based on the assumption that the uncertainty in all measurements of  $Z_{xy}$  is constant; the assumption is based on previous work with similar photodetector arrays.<sup>5</sup> Consequently, the variance in each value of  $R$  is estimated as being proportional to  $Z_{xy}^{-1}$ . The weight for each datum is the reciprocal of the variance.

In order to efficiently utilize the limited memory space of a small computer, the following arrays can easily be built:

$$\begin{array}{ccccc} \sum Z_{xy}^2 & \sum Z_{xy}^2 x & \sum Z_{xy}^2 x^2 & \sum Z_{xy}^2 y & \sum Z_{xy}^2 y^2 \\ \sum Z_{xy}^2 x & \sum Z_{xy}^2 x^2 & \sum Z_{xy}^2 x^3 & \sum Z_{xy}^2 xy & \sum Z_{xy}^2 xy^2 \\ \mathbf{F}'\mathbf{W}\mathbf{F} = \sum Z_{xy}^2 x^2 & \sum Z_{xy}^2 x^3 & \sum Z_{xy}^2 x^4 & \sum Z_{xy}^2 x^2 y & \sum Z_{xy}^2 x^2 y^2, \\ \sum Z_{xy}^2 y & \sum Z_{xy}^2 xy & \sum Z_{xy}^2 x^2 y & \sum Z_{xy}^2 y^2 & \sum Z_{xy}^2 y^3 \\ \sum Z_{xy}^2 y^2 & \sum Z_{xy}^2 xy^2 & \sum Z_{xy}^2 x^2 y^2 & \sum Z_{xy}^2 y^3 & \sum Z_{xy}^2 y^4 \end{array}$$

$$\sum Z_{xy}^2 \ln(Z_{xy})$$

$$\sum Z_{xy}^2 \ln(Z_{xy})x$$

$$\mathbf{F}'\mathbf{W}\mathbf{R} = \sum Z_{xy}^2 \ln(Z_{xy})x^2.$$

$$\sum Z_{xy}^2 \ln(Z_{xy})y$$

$$\sum Z_{xy}^2 \ln(Z_{xy})y^2$$

The following equations yield the parameters which describe the beam:

$$w_x = -1/b_2^{-1/2},$$

$$w_y = -1/b_4^{-1/2},$$

$$p_x = -b_1/2b_2,$$

$$p_y = -b_3/2b_4,$$

$$A = b_0 - b_1^2/4b_2 - b_3^2/4b_4.$$

## VI. RESULTS

The diode array system was used to measure the spatial profile of a mode-locked Nd:YAG laser system. Details of the laser system are given elsewhere.<sup>9</sup> Figure 3 shows the spatial profile of a single picosecond pulse measured with the RA32×32A array. After a background subtraction, the Gaussian parameters were found to be  $w_y = 0.745$  mm and  $w_x = 0.790$  mm ( $y$  is in the vertical plane and  $x$  is in the horizontal plane). Illumination of the diode array by diffuse light showed less than an estimated 7% pixel-to-pixel variation in sensitivity. When each pixel output was normalized to eliminate the 7% pixel-to-pixel sensitivity variations (by dividing by the diffuse light output), the Gaussian parameters were essentially unaffected:  $w_y = 0.749$  mm,  $w_x = 0.794$  mm.

Although statistical parameters can be and are computed to describe the goodness of fit, the primary purpose in doing so is to determine whether the model (Gaussian) is an appropriate one. With the availability of a graphics terminal, a visual evaluation is more effective. The residuals between the least-squares values and the experimental data are com-

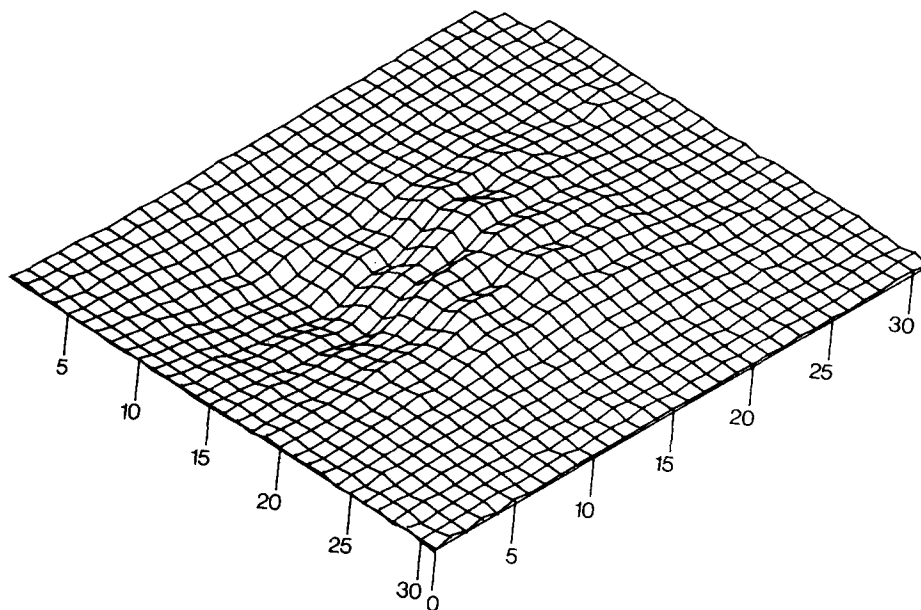


FIG. 4. Residuals after the least-squares fit of the data of Fig. 3 to a Gaussian peak. The vertical scale has been expanded  $10\times$  from that of Fig. 3.

puted and displayed in Fig. 4. If the beams were significantly non-Gaussian, a pattern of one or more concentric rings would be observed. The absence of such a pattern indicates an acceptable model.

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