

# Radiation hard diamond laser beam profiler with subnanosecond temporal resolution

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A two-dimensional detector array has been fabricated from a single 10-mm-diam by 100- $\mu\text{m}$ -thick chemical vapor deposition diamond disk by applying a  $1 \times 1 \text{ mm}^2$  metallization grid of  $4 \times 4$  pixels with centered bias connections. This diamond has been exposed to high power pulsed laser radiation. It has been shown that this kind of diamond array operates as a radiation hard, ultrafast laser beam profiler and can obtain spatial profiles with 500 ps temporal resolution. Ten spatial profiles were obtained within a single 5 ns duration laser pulse, revealing in detail the temporal and spatial development of the laser beam intensity. No attenuation is necessary for this profiler when making single-shot measurements at intensities up to  $\sim 100 \text{ MW/cm}^2$ . © 2002 American Institute of Physics. [DOI: 10.1063/1.1424904]

## I. INTRODUCTION

The technology of laser beam profiling is evolving with the advent of more applications for high power lasers. Examples of applications in which the shape of the beam profile is important range from laser based weapons and sophisticated plasma diagnostics to laser cutting of metals.<sup>1,2</sup> Depending on the accurate alignment within the cavity, laser output power is not evenly distributed over the illuminated area but usually peaks in the center and drops (hopefully monotonically) towards the fringes. This behavior is additionally influenced by the optics used to focus/defocus the beam or to change its direction. To improve the emission profiles by fine tuning the cavity, a fast, rugged beam profiler is needed that is capable of providing data at the repetition rate of the laser. The temporal behavior of the emitted light in the case of a pulsed laser shows similar characteristics, with respect to rise and fall time of laser intensity.

Ideal beam profilers (BPs) should provide nanosecond time resolution, spatial resolution of  $\sim 100 \mu\text{m}$ , and the ability to withstand high incident power to ensure that no additional optics have to be used. Laser profilers available today fall into two categories—nonelectronic and electronic. Nonelectronic profilers lack dynamic range and temporal and spatial resolution. Present state-of-the-art electronic BPs rely either on direct irradiation of pyroelectric arrays and silicon charged coupled devices (CCDs) or on CCDs behind an image converter. These BPs lack temporal resolution and have to be used with beam shaping or attenuating optics to prevent damage to the sensitive detection elements. Additionally, when used with ultraviolet (UV) sources, attenuators and CCD arrays degrade with time. Another disadvantage is that most of these systems use CCD video converters, which limits the rate of laser profile capture to 30 frames/s.

Diamond detectors can overcome these limitations. Diamond, as a possible material for detectors, has been a subject

of considerable interest ever since manufacturing of high quality chemical vapor deposition (CVD) diamond has reduced cost significantly from equivalent natural diamond membranes.<sup>3–5</sup> Diamond detectors were found to have better temporal resolution than Si detectors.<sup>6,7</sup> Others<sup>8,9</sup> have already demonstrated the radiation hardness of diamond. In order to make diamond an adequate tool for laser beam analysis, two-dimensional (2D) detector arrays have to be fabricated. Arrays made from individual diamond pixels are expensive and limited in spatial resolution (to  $\sim 0.25\text{--}0.5 \text{ mm}$ ). However, metallization and lithography processes allow fabrication of 2D arrays with very high spatial resolution ( $\sim 50 \mu\text{m}$ ) on large CVD diamond disks. Today, electronic grade CVD diamond disks are available in diameters up to 100 mm.

Although diamond strip line detectors have been used for x-ray detection in the past, no real 2D arrays were produced on one single diamond. We have assembled a  $4 \times 4$  pixel 2D array and tested it with pulsed Nd:YAG lasers to prove the possibility of using diamond for temporally resolved laser beam profiling.

## II. CONCEPT AND DESIGN

### A. Simple model of diamond conduction

The average energy to produce an electron-hole pair in diamond is estimated to be 13 eV.<sup>10</sup> Thus, the maximum number of electrons produced in diamond by incident radiation is

$$N_e = \beta \cdot N_r \cdot \eta, \quad (1)$$

where  $N_e$  is the number of electrons produced per second,  $\beta = E_r/13 \text{ eV}$  ( $E_r$  = energy of incident radiation quantum),  $N_r$  is the number of radiation quanta incident on the diamond/second, and  $\eta$  the absorption efficiency.

Equation (1) may be written as

$$N_e = \frac{h \cdot \nu}{13 \text{ eV}} \cdot \frac{P_{\text{in}}}{h \cdot \nu} \cdot \eta, \quad (2)$$

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where  $h\nu$  is the energy of the incident photons,  $P_{in}$  is the incident power on the detector surface in W. The induced conduction current  $I=N_e \cdot Q$  is additionally limited by the absorption efficiency, and the fact that the lifetime of the charge carriers ( $T$ ), which is 0.2 ns, might be shorter than their transit time ( $\tau$ ) across the anode-cathode (A-K) gap. Therefore, the current is given by

$$I = \frac{1}{13[V]} \cdot P_{in} \cdot \eta \cdot \frac{T}{\tau} \quad (3)$$

which when we insert the (Beer's law) absorption fraction becomes

$$I = \frac{1}{13} P_{in} (1 - e^{-\alpha d}) \frac{\mu T V_{Bias}}{l^2}, \quad (4)$$

where  $\alpha$  is the absorption coefficient (in  $cm^{-1}$ ),  $\mu$  the charge-carrier mobility ( $1800 \text{ cm}^2/Vs$ ), and  $d$  (cm) and  $l$  (cm) are the thickness and the conduction length of the diamond, respectively.

The active area of one pixel can be estimated by the collection distance<sup>11,12</sup> which is defined as

$$S = \mu \cdot F \cdot T, \quad (5)$$

where  $F$  is the applied electric field. For a bias voltage of 100 V,  $S = 7.2 \times 10^{-4} \text{ cm}$  ( $F = 100 \text{ V}/0.05 \text{ cm}$ ), which results in an active area including the metallized area of each pixel of  $4.15 \times 10^{-5} \text{ cm}^2$ . The metallized area is included because charge carriers produced above the  $50 \mu\text{m} \times 50 \mu\text{m}$  area are collected as well. The dependence of the active area on the applied voltage means that the active pixel area and thereby the sensitivity of this detector can be adjusted by adjusting the bias voltage, limited only by breakdown by surface flash-over from the pixel center to ground. Additionally, this effect limits the pixel-to-pixel crosstalk because an electron created in one pixel cannot travel into a neighboring one. Although the pixel size is limited, the overall detector area is limited only by the diameter of CVD disks, which, as stated earlier, may be up to 100 mm.

This type of detector will work for all wavelengths that can penetrate the thickness of the diamond fully, which includes visible and UV light up to the bandgap of diamond, which corresponds to 223 nm. Below the bandgap all the radiation is absorbed in a very small layer, e.g., for 220 nm radiation [ $\alpha = 1250 \text{ cm}^{-1}$  (Ref. 13)]  $>99\%$  are absorbed within  $36 \mu\text{m}$ . Above the bandgap, absorption is significantly smaller and drops from  $\alpha = 2.1 \text{ cm}^{-1}$  for 266 nm to  $\alpha = 0.23 \text{ cm}^{-1}$  for 532 nm,<sup>14</sup> which implies that only a fraction of the incident radiation (2% for 266 nm,  $<1\%$  for 532 nm) is absorbed within  $100 \mu\text{m}$  of type IIa diamond, which has very similar properties to optical grade CVD diamond used for the profiler.

### B. Experimental arrangement

The monolithic laser beam profiler was made using a 10-mm-diam 100- $\mu\text{m}$ -thick optical grade CVD diamond manufactured by Drukker. The profiler head is divided into two parts. The basic part is the metallized diamond. The

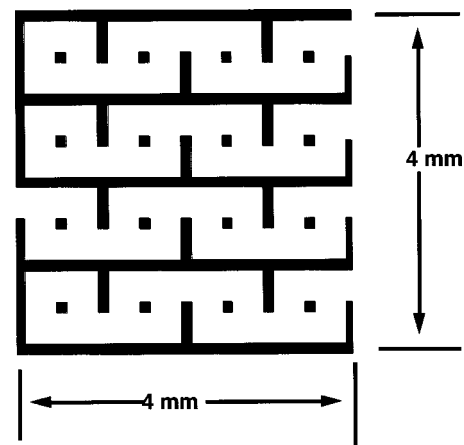


FIG. 1. Schematic of metallization on the rear of the diamond.

metallization is a three layer compound of Ti, Pt, and Au. The pattern, which was metallized on the rear side of the diamond, is shown in Fig. 1.

The centered spots define the high potential applied to each detector element; the black lines are metallized strips at ground potential. After metallization, the diamond was connected with epoxy to the support part, a ceramic plate to provide greater stability. The ceramic has gold striplines metallized on it. Wire bonds were used to connect the metallic tabs on the diamond (both high and ground potential) to different lines on the ceramic.

The metal lines on the ceramic piece were connected using wires to transmission lines etched on a circuit board. These lines were connected to BNC connectors. From the BNC connectors coaxial cables were used to connect to the individual bias boxes and the digitizers. A photograph of the assembled beam profiler/ceramic plate interface is shown in Fig. 2.

The electrode pattern on the diamond was fabricated for us by Sandia National Laboratories as were the wire bonds connecting this electrode pattern to the gold stripes on the ceramic.

### C. Bias circuit

As each pixel in the diamond laser beam profiler has to be biased individually, care must be taken to layout the bi-

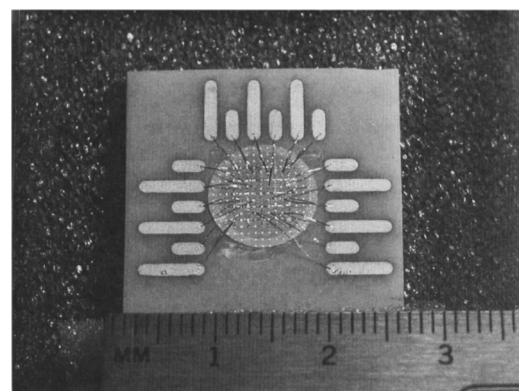


FIG. 2. Profiler/ceramic interface: the scale shows dimension in cm (ceramic plate  $2.6 \times 2.6 \text{ cm}$ ). 18 connections (16 channels and 2 ground).

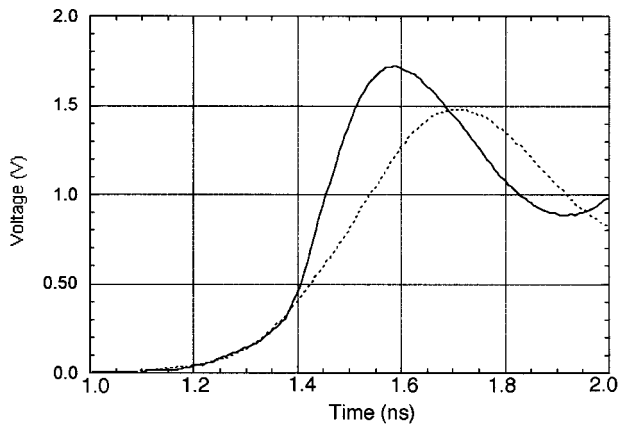


FIG. 3. Data showing a fast pulse measured directly using a Tektronix SCD5000 5 GHz digital oscilloscope (solid) and passing through the detector bias circuit (dashed).

asing circuit. Each pixel requires its own digitizer channel, if no multiplexing technique is used, and its own bias channel. The principle of the bias circuit is very simple. A capacitor is charged via a large ( $>1$  k $\Omega$ ) resistor to the bias voltage. The diamond itself is placed in series with the capacitor and the 50  $\Omega$  input resistance of the digitizer. The moment the diamond becomes conductive a current is driven by the capacitor through the  $R_{\text{diamond}}-C-R_{\text{scope}}$  loop, which is measured as a voltage drop across the input resistor of the digitizer. In the course of an earlier project a 75-channel biasing circuit was designed and fabricated. There was some concern that the close proximity of so many channels might lead to crosstalk. To avoid such problems each channel was housed within its own Faraday shielded enclosure. In addition, due to the use of discrete elements—capacitors and resistors—within each bias channel, there was some concern that the risetime of the circuits might not be adequate to allow  $<1$  ns temporal resolution and good signal-to-noise ratios. These units were tested at Sandia National Laboratory, by the kind courtesy of Dr. Guillermo Loubriel, to determine the risetime of the bias circuits.

A 200 ps risetime pulse from an Avtek pulse generator was passed through the bias circuits. The pulse temporal evolution was measured directly and through the bias circuit at Sandia National Laboratory using a Tektronix SCD5000 5 GHz digital oscilloscope. Figure 3 shows the data. The direct pulse has a 200 ps risetime while the pulse passing through the bias circuit has a 300 ps risetime. The test was repeated with similar results for several channels. It was thus established that the bias circuits are adequate for  $>100$  ps resolution.

### III. TESTS AND RESULTS

A relative calibration of the beam profilers was performed by moving the individual pixels in front of the center of the laser beam with micrometer screws and averaging the result over 1000 pulses because of shot-to-shot fluctuations of the laser. Laser power was measured before and after the averaging to ensure that every pixel was irradiated with the

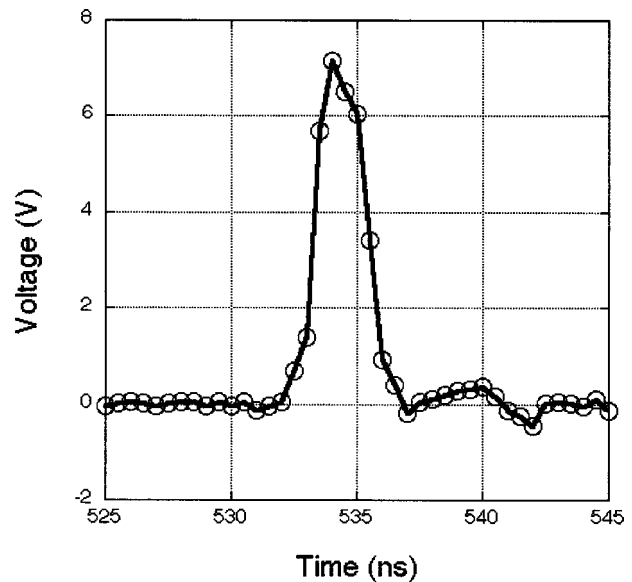


FIG. 4. Sample trace from a single pixel of the monolithic diamond detector.

same light intensity. The sensitivity of the pixels varied by as much as 50%. The obtained calibration factors were taken into account during data analysis.

The diamond detector array was tested at AASC using a Continuum Minilite Nd:YAG laser with 10 mJ output power at 355 nm in a pulse of 5 ns maximum duration. The profiler was irradiated directly—no attenuation was used or needed.

Every pixel was biased with 100 V direct current. The signal from each detector was fed into an oscilloscope (Tektronix TDS 744 and TDS 360 oscilloscopes were simultaneously used to read out 16 channels) with 50  $\Omega$  input impedance. Because the sampling rate of the digitizers was limited to 2 Gs/s, time-resolved measurements were possible down to only a 500 ps sampling time. The profile of the laser was observed to change as a function of time within a single shot.

As an example of how the data are acquired, a sample signal from one pixel is shown in Fig. 4. Shown in this figure is the raw voltage signal into the 50  $\Omega$  input of an oscilloscope. A similar signal was obtained for each pixel on every shot. By using the internal trigger output of the laser and carefully measuring the delay time of all used coaxial cables, all signals could be synchronized. Two-dimensional images of the laser pulse were obtained by taking signal values from each pixel at different times in the laser pulse. A sequence of such images was created for every shot, providing details of the temporal evolution of the laser pulse. More than 500 measurements were taken while varying the laser output and the applied bias voltage.

The data acquired proves that the output power distribution of the laser indeed changes within a single laser pulse. Figure 5 shows the profiles of a single pulse with 500 ps separation. The physical dimension of the images is 4 mm  $\times$  4 mm. The shown data is a result of linear interpolation between two neighboring points to provide smoother images.

Each 2D plot shows the spatial distribution of the laser pulse energy. The pulse can be seen to increase in size and

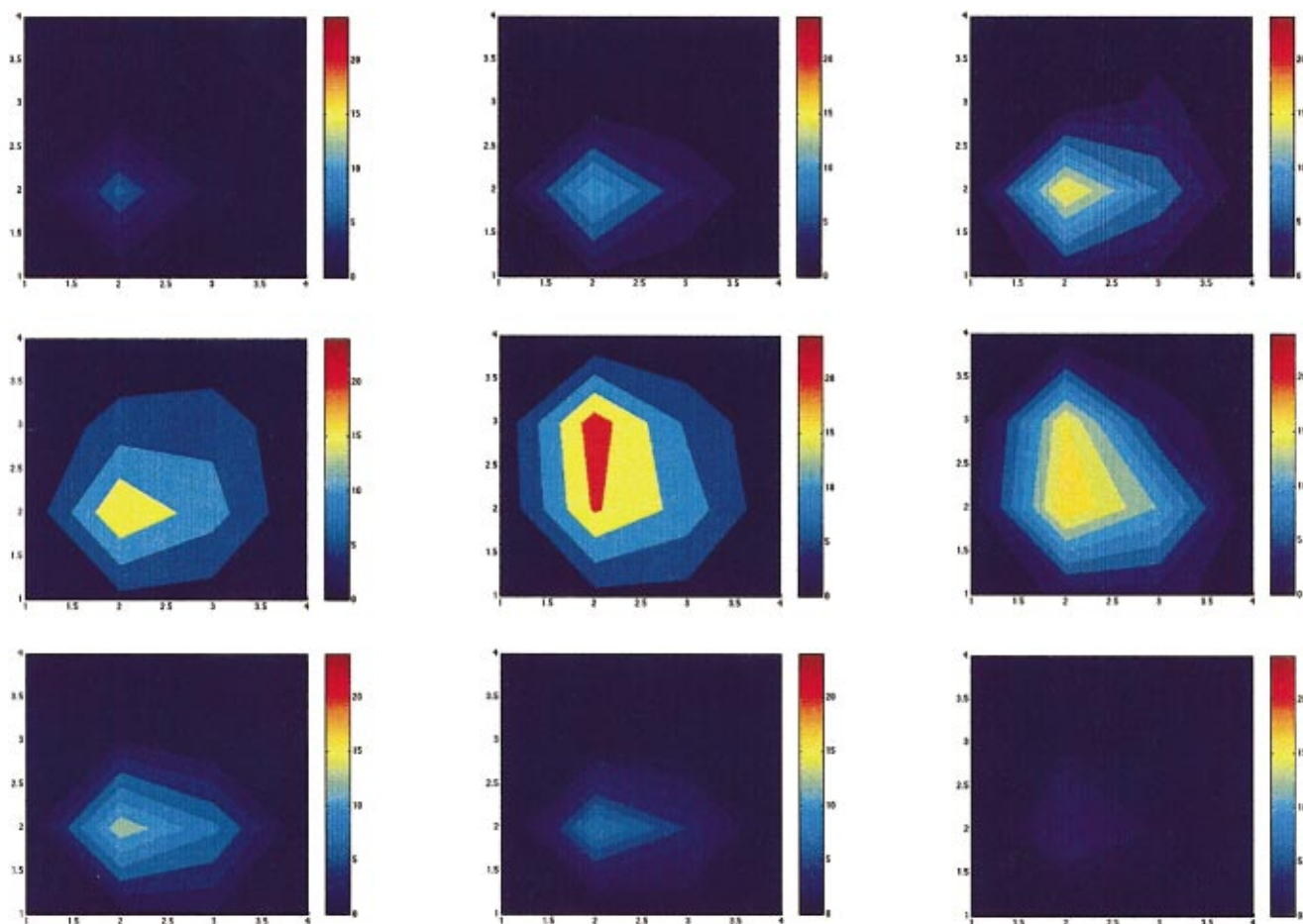


FIG. 5. (Color) Temporal evolution of the intensity distribution during a 5 ns laser pulse. A color bar indicates the level of intensity. Spatial dimensions are in millimeters and time between frames is 0.5 ns.

intensity in time until it reaches its peak value and decays again. A shift of area of maximum intensity can be noted from image 4 to image 5. No sign of gain depletion as reported by Caprara *et al.*<sup>15,16</sup> was found, but this may be due to insufficient spatial resolution.

Radiation hardness of the diamond array has been tested up to  $100 \text{ MW/cm}^2$ . After focusing the beam to an area of  $2 \text{ mm}^2$  parts of the array have been subjected to 1000 pulses. Visual inspection and investigations with an optical microscope have not shown any damage to the diamond or the metallization. The functionality of the array did not change.

#### IV. DISCUSSION

It has been shown that a 2D laser profiler array based on CVD diamond can be fabricated. This array has proven to be suitable for temporally resolved beam profiling of high power laser beams. No attenuation methods have to be employed. Temporal resolution has been shown to be at least 500 ps, limited only by the sampling rate of the digitizers that were used. A spatial resolution of 1 mm has been demonstrated but can easily be improved by using other metallization patterns. Higher spatial resolution is certainly limited by manufacturing and data acquisition. Although pixel sizes of  $50 \mu\text{m}$  or less can be easily manufactured by photolithographic means the capability of reading out a large number of channels is definitely limited. Data transfer of a fairly

large number of channels to a data acquisition unit is possible and has been shown for CCD cameras, but in order to provide the temporal resolution expensive fast digitizer channels are needed. However, this number can be reduced by using multiplexing techniques.

This tool promises to be a major advance over currently used laser beam profilers by providing unprecedented temporal resolution in combination with the relatively high radiation hardness of diamond which has been found by others to be as high as  $1 \text{ GW/cm}^2$ .<sup>17</sup> Even at input levels this high, the metallization on the backside of the diamond is likely to survive due to the use of carbide forming Ti as a first metallization layer, but the diamond would have to be thicker to increase absorption in the diamond bulk.

#### ACKNOWLEDGMENT

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