Photoacoustic technique to measure beam profile of pulsed laser systems

Srivalleesha Mallidi and Stanislav Emelianov

Department of Biomedical Engineering, University of Texas at Austin, Austin, Texas 78712, USA

(Received 16 October 2008; accepted 7 April 2009; published online 8 May 2009)

The beam profiles of pulsed lasers are currently measured using either complementary metal oxide semiconductor (CMOS) or charge coupled device (CCD) cameras. Despite providing high-resolution beam profiles, these devices cannot work with high power lasers. If additional optical attenuators are used, beam distortions may occur. In this paper we demonstrate a high-resolution photoacoustic technique capable of measuring the beam profile of pulsed lasers. The beam profiles of a pulsed neodymium-doped yttrium aluminium garnet (Nd:YAG) laser and a pulsed optical parametric oscillator (OPO) laser system were measured using a polydimethylsiloxane film and a single element high-frequency ultrasonic transducer. The advantages and limitations of the developed photoacoustic technique are discussed. © 2009 American Institute of Physics.

[DOI: [10.1063/1.3125625](https://doi.org/10.1063/1.3125625)]

I. INTRODUCTION

Knowledge of beam profile parameters, such as beam diameter, shape, and power distribution, is essential for the effective use of lasers in many scientific and industrial applications. Mechanical scanning instruments including the knife-edge, slit, pinhole beam profilers, complementary metal oxide semiconductor (CMOS), and charge coupled device (CCD) camera based profilers are commercially available for beam profile measurements. The pinhole/knife-edge models have a resolution closer to 1 μm , but they do not operate in real time for pulsed lasers with a pulse repetition frequency (PRF) of less than 100 KHz. The CMOS/CCD camera based profilers also have good spatial resolution (about 5 μm); however they can accept only low laser power (usually in picowatt range). Additional optical elements used with camera based profilers (to reduce the beam intensity) could cause beam distortions. Here, we demonstrate a high-resolution beam profile measurement technique for pulsed lasers using photoacoustic phenomenon.¹

Photoacoustic transients are produced as part of the interaction between optically absorbing samples and short pulses of laser light that satisfy the thermal-stress confinement condition. An optical absorber irradiated with short pulses of electromagnetic energy, such as light, undergoes thermoelastic expansion and subsequently generates photoacoustic transients. The specific details of the laser generation of ultrasound in solids have been discussed elsewhere.² The characteristics of the photoacoustic transients depend on the Grüneisen parameter, the optical absorption coefficient of the sample, and the incident laser fluence. At a particular temperature and laser wavelength (i.e., the constant Grüneisen parameter and the absorption coefficient of the sample), the amplitude of the photoacoustic response will be proportional to the incident laser energy.³ Therefore, a photoacoustic image of a homogenous thin sample, irradiated with a pulsed laser beam, will represent the laser beam profile.

In this paper, beam profiles of a Q-switched neodymium-doped yttrium aluminium garnet (Nd:YAG) laser operating at

532 nm and an optical parametric oscillator (OPO) laser system operating at 680 nm were imaged using a black polydimethylsiloxane (PDMS) film and a 25 MHz single element focused ultrasound transducer. The results of the experiment were compared to a burn imprint produced by the laser beam on a thermally sensitive paper. Furthermore, experimental studies were performed to compare the performance of the photoacoustic technique with a commercially available laser power meter. Finally, the paper concludes with the discussion of the advantages and limitations of the developed photoacoustic technique.

II. MATERIALS AND METHODS

Thin PDMS films (approximately 150 μm thickness) were fabricated using a procedure described elsewhere.⁴ PDMS was chosen since it has a high thermal expansion coefficient, and researchers have already demonstrated the photoacoustic generation of high-frequency, broadband ultrasound signals using PDMS films.^{4,5} Briefly, a 10:1 mixture of the PDMS prepolymer and curing agent, carbon black dye (1% by weight), and toluene (2% by weight) were thoroughly mixed. The carbon black dye was added to the mixture to elevate the optical absorption of the PDMS film, and the mixture was degassed in a vacuum chamber. The solution was then spin coated onto a microscope glass slide at 500 rpm for 30 s. The film was dried at 80 °C in a vacuum chamber for 8 h and was carefully peeled from the microscope glass slide. The PDMS film thickness was estimated to be approximately 150 μm . The PDMS film was then attached to an elevated stand in a water cuvette with an optical window as shown in Fig. 1(a).

The beam profiles of a Q-switched Nd:YAG laser (Polaris II, New Wave Research, Inc., 532 nm wavelength, 5 ns pulse duration, 20 Hz PRF, and 12 mJ/cm^2 incident fluence) and a tunable OPO laser system (Vibrant, OPOTEK, Inc., 680 nm, 7 ns pulse duration, 10 Hz PRF, and 10 mJ/cm^2 incident fluence) were measured. While the Gaussian beam profile was expected from the Nd:YAG laser, the OPO laser

FIG. 1. (Color online) (a) Schematic representation and (b) block diagram of the experimental setup for laser beam profile measurement using photoacoustic phenomenon.

system in contrast was slightly misaligned and produced a non-Gaussian beam. The laser beam was projected onto the PDMS film through a commercially available fused silica optical window, which was on the bottom of the water cuvette.

A single element focused ultrasound transducer (25 MHz center frequency, 60% fractional bandwidth, 12.6 mm focal length, and 6.3 mm aperture size corresponding to approximately $120\ \mu\text{m}$ lateral resolution and $50\ \mu\text{m}$ axial resolution), mounted on a three dimensional (3D) positioning stage, was used to capture the photoacoustic transients [Fig. 1(b)]. The transducer position was then adjusted so that the PDMS film was located in the focal region of the ultrasound transducer. This adjustment was made to ensure that the photoacoustic response was measured only from the cross-sectional area of the PDMS film, defined by the width of the ultrasound beam as shown in Fig. 1(a). To measure the entire profile of the laser beam, the transducer was mechanically scanned over the desired two dimensional (2D) region. To satisfy Nyquist sampling criterion, the scanning was performed in steps of $40\ \mu\text{m}$ corresponding to one-third of the lateral resolution of the ultrasound transducer.

The synchronous trigger from the laser commenced the data acquisition [Fig. 1(b)]. At each position, 20 photoacoustic A-lines were acquired using an 8 bit, 500 MHz digitizer and then averaged to improve the signal-to-noise ratio (SNR) of the signals. During the offline processing, a digital band-pass (5–45 MHz) filter was applied to the photoacoustic

FIG. 2. (Color online) Schematic representation of the experimental setup to obtain different laser fluencies irradiating the PDMS film.

signals to reduce the noise. The analytic signals were obtained by applying a Hilbert transform on the filtered radio-frequency (rf) signals. An array containing the maximum value of the analytic signal at each scan position was formed. Additionally, a 5×5 median filter was applied to this array data to minimize spurious noise due to the fluctuations in the laser beam intensity. Finally, the image was formed using the array data to represent the beam profile of the laser.

The range of laser fluencies that can be measured using the photoacoustic technique was determined by slightly modifying the experimental setup shown in Fig. 1(a). Due to the unavailability of lasers with different output fluencies, the 15 mJ laser beam from the Nd:YAG laser was projected onto the PDMS film through a biconvex lens attached to a vertical positioning system. As shown in the schematic representations in Fig. 2, the distance between the PDMS film and the biconvex lens was adjusted to obtain a range of laser fluencies ($0.080\text{--}700\ \text{mJ/cm}^2$) irradiating the film. The amplitude of the photoacoustic response obtained from the PDMS film was recorded and analyzed as a function of laser fluence.

Finally, the performance of the photoacoustic beam profile measurement technique was compared to commercially available laser power meter (Nova II, Ophir Optonics, Ltd.). The power meter was synchronized to the photoacoustic data acquisition system [Fig. 1(b)] using a LabVIEW program. A 50:50 beamsplitter cube was used to split the laser beam from the OPO operating at 800 nm wavelength. The reflected laser beam was used to obtain the measurements from the laser power meter, and transmitted beam was used to obtain the photoacoustic response from the PDMS film. Data from 200 laser pulses were recorded to assess the performance of the photoacoustic measurement technique.

III. RESULTS

A segment of the typical A-line containing the photoacoustic rf signal generated from a PDMS film illuminated with 5 ns laser pulse is shown in Fig. 3 (solid line). The dashed line in Fig. 3 represents the absolute value of the analytic signals obtained by applying a Hilbert transform on the rf signals. Since the maximum value of the analytic signal depends on the laser fluence incident on the PDMS film, this value was calculated for each scan position to obtain the laser pulse profile.

FIG. 3. (Color online) Photoacoustic rf signal (solid line) generated by illuminating a PDMS film with a 5 ns laser pulse. The absolute value of the analytic signal (dashed line) obtained by applying a Hilbert transform to the rf data.

The beam profile of the Nd:YAG laser, operating at 532 nm wavelength, is shown in Fig. 4(a). This 2D beam profile [Fig. 4(a)], normalized to the highest intensity within the image, is displayed over a 10%–100% range. The scale is chosen so that black represents the smallest intensity (low photoacoustic signal amplitude) and white represents the largest laser intensity (high photoacoustic signal amplitude). The imprint of the laser beam on photographic burn paper is also presented in Fig. 4(b). The burn paper has a nonlinear response to the incident laser energy, and therefore, the laser beam imprint on the burn paper cannot be directly compared to the beam profile shown in Fig. 4(a). The 1D profiles of laser intensity along the horizontal and vertical lines, passing through the center of the image in Fig. 4(a), are plotted in Figs. 4(c) and 4(d), respectively. As expected from manufacturer specifications, the 1D laser intensity profiles [solid line in Figs. 4(c) and 4(d)] and the Gaussian fit of the data [dotted

FIG. 4. (Color online) (a) The 2D beam profile of the Nd:YAG laser operating at 532 nm wavelength obtained using photoacoustic technique and (b) laser beam imprint on a burn paper. Quantitative 1D profiles of the laser beam (solid line) and Gaussian fit of the data (dotted line) measured along (c) the horizontal ($Y=1.4$ mm) and (d) vertical ($X=1.4$ mm) lines.

FIG. 5. (Color online) (a) The 2D beam profile of the misaligned OPO laser system operating at 680 nm wavelength obtained using photoacoustic technique, (b) laser beam imprint on burn paper, and quantitative 1D profiles of the laser beam measured along (c) the horizontal ($Y=8$ mm) and (d) vertical ($X=8$ mm) lines.

line in Figs. 4(c) and 4(d)] clearly indicate the beam of the Nd:YAG laser used in our experiment exhibits a Gaussian profile.

The laser beam profile of the OPO laser system, operating at a wavelength of 680 nm, is shown in Fig. 5. Overall, the photoacoustic beam profile [Fig. 5(a)] and imprint on burn paper [Fig. 5(b)] were similar. The non-Gaussian beam outputted from the misaligned OPO laser system used in the experiment consisted of two entwined lobes, with more energy concentrated in one of the lobes, as seen in Fig. 5.

The variation in the photoacoustic signal amplitude with respect to the laser fluence is shown in Fig. 6. The error bars indicate the standard deviation obtained from 50 laser pulses. The dashed line is a linear fit $p=0.4F+0.047$ of the experimental data, where p denotes photoacoustic signal amplitude and F represents the laser fluence. The zoomed version of the rectangular inset in Fig. 6(a) is shown in Fig. 6(b), and the zoomed version of the rectangular inset in Fig. 6(b) is shown in Fig. 6(c). Clearly the graphs in Fig. 6 show a linear relationship between the laser fluence and the amplitude of the photoacoustic response from the PDMS film. Theoretically if the input laser fluence is zero, no photoacoustic signal will be generated. However, the linear data fit model shown in Fig. 6 has a positive intercept. This nonzero intercept value is due to the electric noise inherent to receiver electronics and data acquisition system. Further, the slope of the linear data fit model shown in Fig. 6 corresponds to the product of the Grüneisen parameter, the optical absorption coefficient of the sample, and the sensitivity of the ultrasonic detector.

The maximum fluence that could be recorded using the experimental setup shown in Figs. 1(a) and 2, without damaging the PDMS film, was approximately 300 mJ/cm^2 . A photoacoustic response was also obtained for laser fluence at approximately 700 mJ/cm^2 ; however the PDMS film was damaged. The laser damage threshold of PDMS film re-

FIG. 6. (Color online) The dependence of photoacoustic signal amplitude as a function of the laser fluence. The circles represent the averaged values, and the error bars indicate the standard deviation of the data obtained from 50 observations. The dashed line represents the linear fit of the experimental data. The zoomed version of the rectangular insets in graphs (a) and (b) are shown in graphs (b) and (c), respectively.

ported in literature is in good agreement with the observations in our experimental setup. Specifically, undoped PDMS has high optical absorbance (approximately $0.5 \times 10^5 \text{ cm}^{-1}$) at optical wavelength of 266 nm (Ref. 6) and low optical absorbance in the visible spectrum.⁷ The reported damage threshold fluence at 266 nm wavelength for an undoped PDMS film (thickness 250 μm) was approximately 470 mJ/cm^2 .⁶ The reported values of the optical absorption coefficient of carbon black at 532 nm are approximately in the range of $0.25 \times 10^5 - 1 \times 10^5 \text{ cm}^{-1}$.⁸ The carbon black doped PDMS film used in this study has high optical absorbance (similar to absorbance of undoped PDMS at 266 nm), and hence the laser fluence of 700 mJ/cm^2 caused damage to the PDMS film. The details of the damage caused to the PDMS film are beyond the scope of the paper and have been discussed elsewhere.^{6,9}

The laser fluence of 100 pulses measured using the power meter (dotted line) and photoacoustic measurement technique (solid line) is shown in Fig. 7. Clearly, there is a

FIG. 7. (Color online) Comparison of the laser fluence measurements using photoacoustic measurement technique (solid line) and commercially available laser power meter (dotted line) for 100 laser pulses.

good agreement between the two laser fluence measurement techniques. To quantitatively analyze the data, a scatter plot of laser fluence from 200 pulses measured using the power meter and the photoacoustic measurement technique is shown in Fig. 8. A regression analysis of the data (solid line in Fig. 8) gave a correlation coefficient of 0.85, indicating good agreement between two techniques. Indeed, Figs. 7 and 8 clearly indicate that the accuracy and repeatability of the photoacoustic measurement technique are at par with the commercially available power meter. Similar results were obtained using Nd:YAG laser and OPO laser operating at 680 nm.

IV. DISCUSSION AND CONCLUSION

We have presented a technique to measure the beam profile of pulsed lasers using photoacoustic phenomenon. The advantage of this technique is that it can measure the beam profiles of pulsed lasers with high spatial resolution and over a wide range of laser fluencies. The photoacoustic signal generated is proportional to the laser fluence, the volumetric thermal expansion coefficient, and the absorption coefficient of the detector film (PDMS).³ Since both the volumetric thermal expansion coefficient⁴ and the absorption coefficient of the detector film remain constant during the measurement of the beam profile of a laser operating at a particular wave-

FIG. 8. (Color online) Scatter plot comparing the laser energy measurements obtained using photoacoustic measurement technique and commercially available laser power meter for 200 laser pulses. The solid line is the linear regression fit of the data and the dotted lines represent the 90% confidence intervals.

length, the photoacoustic signal depends only on the incident laser fluence. We have clearly demonstrated the linear working range (tens of $\mu\text{J}/\text{cm}^2$ to hundreds of mJ/cm^2) of the photoacoustic measurement technique using the experimental setup shown in Figs. 1(a) and 2. Indeed by varying the doping levels of carbon black in the PDMS film, the sensitivity of the experimental setup can be increased. The PDMS films can also be doped with metal nanoparticles for wavelength specific beam profile measurements. The sensitivity of the technique can be improved by using high sensitivity ultrasound transducers and receiver electronics with high SNR. Moreover, it has to be noted that photoacoustic technique can be used to measure a wide range of fluencies without use of additional optical attenuators or diffusers.

The spatial resolution of the laser beam profiles presented in Figs. 4(a) and 5(a) is dependent on the beam width of the single element focused ultrasonic transducer, which was used to acquire the photoacoustic signals. The beam width is in turn dependent on the central frequency and f -number of the focused ultrasonic transducer.^{10–12} For the 25 MHz transducer used in our experiments, the spatial resolution within the sensor plane was approximately 120 μm . Resolution on the order of few micrometers can be obtained using low f -number, high frequency ultrasound transducers.

The experimental system presented in this paper does not operate in real time. The laser beam fluctuations were minimized by acquiring 20 signals at each position and applying a median filter during the offline processing of signals. Moreover, mechanical scanning of the single element transducer is not desired. A 2D array of ultrasound transducers can be the solution to the above limitations of a mechanically scanned single element ultrasound transducer. Recent studies have shown the utility of 2D array transducers for ultrasound and photoacoustic^{5,13,14} imaging. Also, the water cuvette used in the current setup can be eliminated using an integrated probe with a detection film and a 2D ultrasonic transducer incorporated together. Optical detection of the photoacoustic transients could also be used for laser beam

profile measurements.¹⁵ Further investigation regarding detection films with high laser damage threshold needs to be performed. In conclusion, we have demonstrated the utility of the photoacoustic technique to provide quantitative, 2D spatially resolved beam profile measurement of pulsed lasers.

ACKNOWLEDGMENTS

Partial support from the National Institutes of Health under Grant Nos. EB004963, HL084076, and EB008101 is gratefully acknowledged. The authors would like to thank Dr. Andrei Karpiouk and Ms. Bo Wang of the University of Texas at Austin for their valuable inputs regarding the system design and fabrication of the PDMS films used in the study.

¹A. G. Bell, *Science* **os**–2, 242 (1881).

²S. J. Davies, C. Edwards, G. S. Taylor and S. B. Palmer, *J. Phys. D* **26**, 329 (1993).

³A. Oraevsky and A. Karabutov, in *Biomedical Photonics Handbook*, edited by T. Vo-Dinh (CRC, Boca Raton, Florida, 2003), Vol. PM125, Chap. 34, pp. 34/31–34/34.

⁴T. Buma, M. Spisar, and M. O'Donnell, *Appl. Phys. Lett.* **79**, 548 (2001).

⁵T. Buma, M. Spisar, and M. O'Donnell, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **50**, 1161 (2003).

⁶V.-M. Graubner, R. Jordan, O. Nuyken, T. Lippert, M. Hauer, B. Schnyder, and A. Wokaun, *Appl. Surf. Sci.* **197–198**, 786 (2002).

⁷J. Xu, X. H. Huang, N. L. Zhou, J. S. Zhang, J. C. Bao, T. H. Lu, and C. Li, *Mater. Lett.* **58**, 1938 (2004).

⁸C. Jäger, T. Henning, R. Schlogl, and O. Spillecke, *J. Non-Cryst. Solids* **258**, 161 (1999).

⁹K. Rubahn, J. Ihlemann, G. Jakopic, A. C. Simonsen, and H. G. Rubahn, *Appl. Phys. A: Mater. Sci. Process.* **79**, 1715 (2004).

¹⁰N. Cohn, S. Emelianov, M. Lubinski, and M. O'Donnell, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **44**, 1304 (1997).

¹¹F. S. Foster, C. J. Pavlin, G. R. Lockwood, L. K. Ryan, K. A. Harasiewicz, L. Berube, and M. A. Rauth, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **40**, 608 (1993).

¹²M. Xu and L. V. Wang, *Phys. Rev. E* **67**, 056605 (2003).

¹³A. Austeng and S. Holm, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **49**, 1087 (2002).

¹⁴Ö. Oralkan, A. S. Ergun, C. Ching-Hsiang, J. A. Johnson, M. Karaman, T. H. Lee, and B. T. Khuri-Yakub, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **50**, 1581 (2003).

¹⁵E. Zhang, J. Laufer, and P. Beard, *Appl. Opt.* **47**, 561 (2008).