REVIEW OF SCIENTIFIC INSTRUMENTS **80**, 035101 (2009)

Pulse shaping of transversely excited atmospheric CO_2 laser using a simple plasma shutter

Noah Hurst[1,2,a] and S. S. Harilal[1,3]
[1]*Hyperion Scientific, Inc., 455 Science Dr., Madison, Wisconsin 53711, USA*
[2]*College of Engineering, University of Wisconsin, Madison, Wisconsin 53706, USA*
[3]*School of Nuclear Engineering, 400 Central Dr., Purdue University, West Lafayette, Indiana 47907, USA*

(Received 10 December 2008; accepted 20 January 2009; published online 3 March 2009)

The pulse from a transversely excited atmospheric CO_2 laser consists of a sharp spike followed by a long, drawn out tail region spanning about 2–5 μs caused by the nitrogen gas in the laser cavity. The nitrogen tail is undesirable in many applications because it decreases the average power of the laser pulse. We employ a pinhole plasma shutter for eliminating the nitrogen tail and shortening the pulse width. The pinhole shutter optically triggers plasma at a certain point in time with respect to the temporal profile of the laser pulse. This way, a good portion of the sharp spike is transmitted, while the energy stored in the nitrogen tail is consumed in heating the plasma. This simplistic plasma shutter is easy to build and inexpensive compared to other existing plasma shutter designs. © *2009 American Institute of Physics.* [DOI: 10.1063/1.3079698]

I. INTRODUCTION

The TEA (transversely excited atmospheric) CO_2 laser pulse temporal profile typically has a tall, sharp spike followed by a long, drawn out nitrogen tail. Although the amplitude of the nitrogen tail is not nearly as high as the initial spike, the tail is drawn out over a time interval of 2–5 μs and holds up to two-thirds of the total energy of the pulse. The nitrogen tail occurs due to the long lifetime of the nitrogen molecule vibrational energy level used to excite the CO_2 molecules and initiate lasing. A sufficient number of nitrogen molecules remain excited after the initial spike to continue the lasing process at a lower power level for the duration of the tail.

Pulsed TEA CO_2 lasers are extensively used in various applications including light detection and ranging (LIDAR), laser ablation material processing, surface cleaning, medical surgery, etc.[1,2] Very recently the TEA CO_2 laser has been used for creating efficient, debris-free extreme ultraviolet (EUV) laser-produced plasma sources; this is considered to be the source for next generation EUV lithography.[3,4] Most of the above applications of the TEA CO_2 laser require high laser power, and the nitrogen tail in the CO_2 laser reduces effective laser power. Several methods have previously been employed to remove the long tail of the pulsed CO_2 laser, including *Q*-switching[5] and the breakdown plasma shutter.[6–10] The crystal used for *Q*-switching of CO_2 infrared laser pulses usually absorbs a large portion of CO_2 energy, hence amplifier stages are necessary for obtaining high peak power.[5] Instead, by using a plasma shutter, one can truncate the laser pulse at a certain point in time so as to transmit the high-power initial spike and block the low-power nitrogen tail, therefore increasing the average power of the laser pulse.

A few successful plasma shutter designs exist,[6–10] but each is complicated and expensive. One plasma shutter technique involves a beam splitter;[6,7] a portion of the laser beam is split off, delayed, and then used to trigger the plasma and clip the nitrogen tail. For a pulse with a full width half maximum (FWHM) of 65 ns, the triggering beam must be delayed by roughly 100 ns; this requires a path difference of 30 m between the two beams. Another plasma shutter design involves a spark gap,[7,8] in this case, the laser pulse is focused in between electrodes and a precisely timed electrical discharge is used to initiate the plasma and truncate the laser pulse. This process requires a very precise timing device and a high-voltage electrical pulse generator. The plasma shutter may also be built with a gas chamber.[9] Here the laser beam is focused into a chamber filled with pressurized gas such as helium, argon, or even air. Breakdown occurs inside the gas chamber and the resulting plasma consumes the energy from the nitrogen tail. However, this method requires a pressure chamber and a gas supply. These methods may be combined, for example, electrodes may be placed in a chamber with a pressurized gas.[10] In this manner, breakdown occurs due to electrical discharge, but is facilitated by the pressurized gas in the chamber. This design requires a pressure chamber as well as a timing generator and high-voltage electrical pulse generator. The plasma shutter detailed in this paper successfully clips the pulse in a much simpler fashion.

II. EXPERIMENT

The TEA-CO_2 laser emits at 10.6 μm and has a maximum energy output of 1 J/pulse. The laser was operated with a 1 cm diameter aperture installed in the laser cavity. The aperture restricts the beam diameter to 1 cm and reduces the nitrogen tail, but fails to eliminate it completely. The laser was pumped through transverse electric discharge at 24 kV and the gas composition (He:N:CO_2) was 6:1:3. Laser pulse energy and stability were studied and it was found that the

---

[a] Electronic mail: nhurst@wisc.edu.

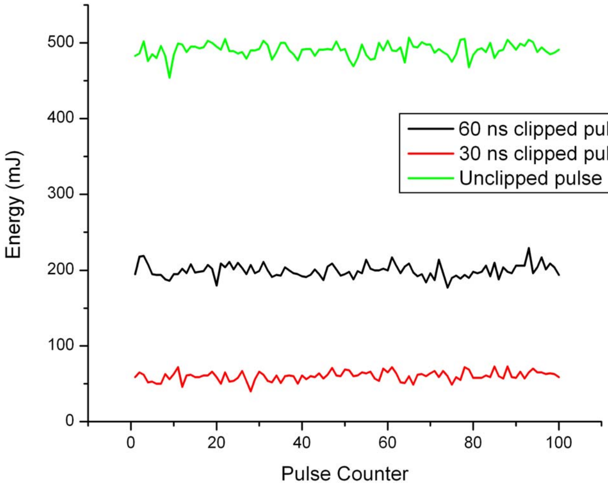

FIG. 1. (Color online) Pulse stability over 100 consecutive pulses for 30 and 60 ns clipped pulses and the unclipped pulse.

mean pulse energy was 490 mJ; the standard deviation in energy was ±9 mJ as shown in Fig. 1. A typical temporal profile for the unclipped pulse is given in Fig. 2.

By integrating the laser pulse temporal profile curve and estimating the boundary between the initial spike and the nitrogen tail, the energy distribution between the two separate portions of the pulse was approximated. It was found that the initial spike contained 35%–40% of the total pulse energy, while the nitrogen tail contained 60%–65% of the energy. Based on the 490 mJ mean pulse energy, the initial spike contains approximately 172–196 mJ and the nitrogen tail contains approximately 294–319 mJ. FWHM pulse width of the initial spike is around 65 ns. Assuming the nitrogen tail extends over about 2 μs, average power is 2.65–3.01 MW for the initial spike and 0.147–0.160 MW for the nitrogen tail. In applications such as CO_2 laser produced plasma sources, where laser pulse peak power is a critical factor, the plasma shutter should be installed to absorb energy from the nitrogen tail and transmit energy from the initial spike to maximize the average power of the laser pulse.

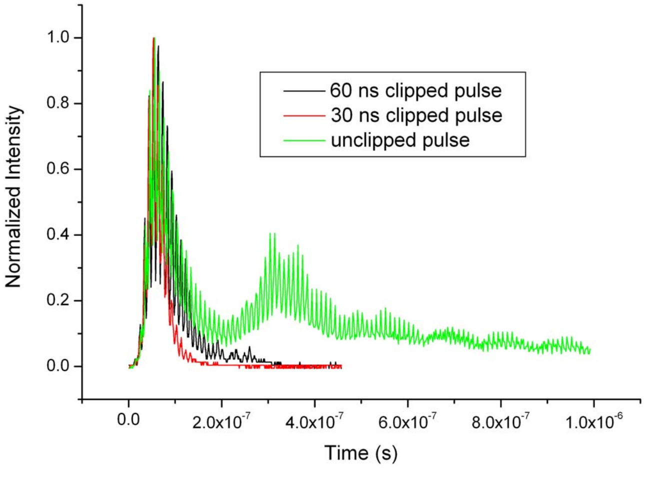

FIG. 2. (Color online) Temporal profiles of 30 ns, 60 ns, and unclipped pulses. Note the similarity between 60 ns clipped pulse and initial spike of unclipped pulse.

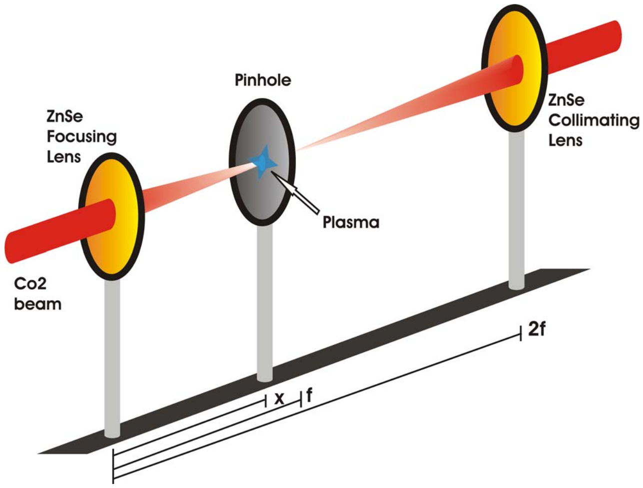

FIG. 3. (Color online) Plasma shutter diagram. The focal length is f and x represents the distance from the focusing lens to the pinhole. Distance x was varied by sliding the pinhole back and forth along the optical rail.

The plasma shutter consists of a focusing lens, a pinhole, and a collimating lens mounted on an optical rail. The laser beam passes through the focusing lens, forms a plasma at the pinhole, and the transmitted, diverging pulse is collimated by another lens, as shown in Fig. 3. ZnSe planoconvex lenses with 1 in. diameter and focal length of 40 cm were used to focus and collimate the laser beam. The 1 mm diameter pinhole was placed at or in front of the focal point of the focusing lens. The collimating lens has the same focal length as the focusing lens and was placed at exactly twice the focal length away from the focusing lens in order to perfectly collimate the laser beam after exiting the plasma shutter system.

III. RESULTS AND DISCUSSION

As the focused laser beam passes through the pinhole, the power density resulting from the initial spike of the CO_2 pulse should be high enough to form plasma from the pinhole material and the surrounding air. If this plasma can be formed at a certain point in time, the nitrogen tail can be clipped and the initial spike transmitted. Spot diameter at the focal length is determined by Eq. (1),

$$d = \frac{4\lambda f M^2}{\pi D}, \tag{1}$$

where M^2 is related to the divergence of the laser beam (~ 2), λ is the wavelength of the incident light, f is the focal length, d is the final beam diameter, and D is the initial beam diameter. This equation gives a spot diameter of 1.08 mm.

The CO_2 laser pulse focused at 40 cm has a power density of the order of 10^8 W/cm^2, while the reported breakdown threshold of air is of the order of 10^9 W/cm^2 for 10.6 μm radiation.[11] The pinhole facilitates plasma initiation by providing starting electrons for the avalanche ionization process for gas breakdown.[6] Furthermore, the spot size incident on the pinhole target may be increased by positioning the pinhole slightly closer to the focusing lens as shown in Fig. 4. This leads to earlier breakdown at the pinhole and therefore earlier pulse clipping. In this manner, the plasma

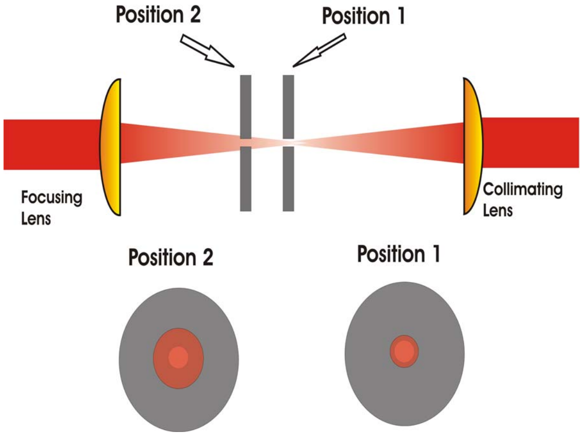

FIG. 4. (Color online) Schematic of the pinhole at two different positions with respect to the focusing lens. The bottom of the graphic shows a view along the axis of the laser beam. Position 1: the pinhole is situated at the focal length where spot size is at a minimum. A minimum portion of the laser beam spatial profile is incident on the pinhole metal. Position 2: the pinhole is situated some distance away from the focal point, toward the focusing lens. A greater portion of the beam collides with the pinhole metal and therefore plasma is formed earlier.

shutter user may shorten output pulse width by sliding the pinhole toward the focusing lens on the optical rail.

The two lenses were aligned without the pinhole so that the laser beam would pass straight through the center of each lens. The lenses were placed exactly 80 cm apart and remained fixed for the rest of the experiment. Then the pinhole was inserted between the lenses. A 1 mm diameter pinhole was used because it is similar to the calculated spot size (1.08 mm). Larger pinhole diameters were tested (1.5 and 2 mm), but these pinholes allowed complete transmission of the laser pulse without clipping the nitrogen tail at all when positioned at or near the focal point. Aluminum was used for the pinhole material. A copper pinhole was also tested, but did not clip the laser pulse as effectively and reliably as the aluminum pinhole. The pinhole was placed at the focal point and aligned perfectly with the optical axis so that transmitted energy was at a maximum. The pinhole was then translated along the optical axis toward the focusing lens in order to decrease the pulse width. Using this method we were able to vary the pulse width of the laser from 25–60 ns. The pulse stability of 30 and 60 ns pulses obtained with the plasma shutter is given in Table I. Pulse energy was recorded over 100 consecutive pulses for each pulse width to monitor stability (Fig. 1).

It was estimated that the initial spike from the unclipped pulse held about 172–196 mJ and had a FWHM of about 65 ns. It was experimentally observed that the 60 ns clipped pulse held an average of 199 mJ. Standard deviation in energy for the unclipped pulse was ±9 mJ, and ±8.7 mJ for the clipped pulse. Typical unclipped and clipped FWHM 60 ns pulse profiles are given in Fig. 2. The clipped 60 ns pulse was strikingly similar to the initial spike from the unclipped pulse in pulse width, energy, and stability. The average energy in the clipped pulse was slightly higher than the energy range of the initial spike in the unclipped pulse, possibly due to the error involved in integrating the unclipped pulse. The boundary between the initial spike and the nitrogen tail was approximated at the local minimum of the signal between the two regions. It can be seen that the clipped pulse contains a small amount of energy beyond the approximated border, which may account for extra energy observed in the clipped pulse.

TABLE I. Properties and statistics of 30 and 60 ns clipped pulses.

Distance from lens to pinhole (cm)	37.5	31.75
Mean pulse energy (mJ)	199.5	60.3
Standard deviation in pulse energy (mJ)	±8.6	±6.3
FWHM of laser pulse (ns)	60±3	30±2
Mean pulse peak power (MW)	3.3	2

The plasma shutter will function until the thin aluminum pinhole wears down due to laser ablation. However, the thickness of the aluminum sheet metal used for the pinhole was about 250 μm and no failure effects were observed after more than a month of frequent operation (~10 000 laser pulses). In addition, if failure eventually occurs over a longer time span, replacement aluminum pinholes will be very inexpensive. In fact, the lifetime of the pinhole depends on the selection of laser pulse width after clipping. The pinhole will last longer if used for truncating the nitrogen tail alone. However, more ablation can be expected to the pinhole aperture if the plasma shutter is used for obtaining shorter pulses (25–50 ns). For shorter pulses, more energy must be blocked by the pinhole; the resulting higher power density incident on the pinhole will cause shorter lifetime.

IV. CONCLUSIONS

A simple plasma shutter was designed for clipping the nitrogen tail from the carbon dioxide laser pulse. The simple, inexpensive plasma shutter design consisted of only two lenses, a small disk of aluminum, and an optomechanical mounting equipment. The laser beam passes through the focusing lens, forms a plasma at the pinhole, and the transmitted, diverging pulse is collimated by another lens. The nitrogen tail was effectively clipped and the initial spike completely transmitted without sacrificing pulse energy stability. The FWHM of the laser pulse can be varied from 25–60 ns by selecting a proper separation between the focusing lens and pinhole. Pinhole lifetime is higher than 10 000 pulses, and replacement pinholes are inexpensive.

ACKNOWLEDGMENTS

The authors thank National Science Foundation for partially supporting this project through the REU program.

[1] O. A. Romanovskii, Proc. SPIE **6594**, 65940C (2007).
[2] M. Ivanenko, M. Werner, S. Afilal, M. Klasing, and P. Hering, Med. Laser Appl. **20**, 13 (2005).
[3] A. Endo, H. Hoshino, T. Suganuma, K. Nowak, T. Yanagida, T. Yabu, T. Abe, and K. Toyoda, Proc. SPIE **6703**, 670309 (2007).
[4] A. Endo, H. Hoshino, T. Suganuma, K. Nowak, T. Yanagida, T. Yabu, T. Asayama, Y. Ueno, M. Nakano, T. Nishisaka, T. Abe, H. Komori, H. Mizoguchi, A. Sumitani, and K. Toyoda, Proc. SPIE **6921**, 69210T (2008).
[5] H. Hoshino, T. Suganuma, T. Asayama, K. M. Nowak, M. Moriya, T. Abe, A. Endo, and A. Sumitani, Proc. SPIE **6921**, 692131 (2008).
[6] H. S. Kwok and E. Yablonovitch, Opt. Commun. **21**, 252 (1977).
[7] J. Knittel, D. P. Scherrer, and F. K. Kneubuhl, IEEE J. Quantum Electron.

32, 2058 (1996).

[8] C. Bellecci, I. Bellucci, P. Gaudio, S. Martellucci, G. Petrocelli, and M. Richetta, Rev. Sci. Instrum. **74**, 1064 (2003).

[9] T. Gasmi, H. A. Zeaiter, G. Ropero, and A. Gonzalez Urena, Appl. Phys. B: Lasers Opt. **71**, 169 (2000).

[10] Y. Qu, X. Hu, D. Ren, B. Zhou, and W. Song, Proc. SPIE **4914**, 273 (2002).

[11] P. Woskoboinikow, W. J. Mulligan, H. C. Praddaude, and D. R. Cohn, Appl. Phys. Lett. **32**, 527 (1978).