Pramana – J. Phys. (2017) 88: 33
DOI 10.1007/s12043-016-1334-3

Performance characteristics of an excimer laser (XeCl) with single-stage magnetic pulse compression

N K VARSHNAY, A SINGH and N S BENERJI*

Excimer Laser Section, Laser Material Processing Division, Raja Ramanna Centre for Advanced Technology, Indore 452 013, India
*Corresponding author. E-mail: nsb@rrcat.gov.in

MS received 21 December 2015; revised 23 May 2016; accepted 20 July 2016; published online 10 January 2017

Abstract. Performance characteristics of an excimer laser (XeCl) with single-stage magnetic pulse compression suitable for material processing applications are presented here. The laser incorporates in-built compact gas circulation and gas cooling to ensure fresh gas mixture between the electrodes for repetitive operation. A magnetically coupled tangential blower is used for gas circulation inside the laser chamber for repetitive operation. The exciter consists of C–C energy transfer circuit and thyratron is used as a high-voltage main switch with single-stage magnetic pulse compression (MPC) between thyratron and the laser electrodes. Low inductance of the laser head and uniform and intense pre-ionization are the main features of the electric circuit used in the laser. A 250 ns rise time voltage pulse was compressed to 100 ns duration with a single-stage magnetic pulse compressor using Ni–Zn ferrite cores. The laser can generate about 150 mJ at ∼100 Hz rep-rate reliably from a discharge volume of 100 cm^3. 2D spatial laser beam profile generated is presented here. The profile shows that the laser beam is completely filled with flat-top which is suitable for material processing applications. The SEM image of the microhole generated on copper target is presented here.

Keywords. XeCl excimer laser; magnetic pulse compressor; saturable inductor; micro-machining.

PACS No. 42.55.lt

1. Introduction

UV pre-ionized discharge pumped excimer (XeCl) laser systems with ∼100 mJ output pulse energy and ∼100 Hz rep-rate with good beam quality are most popular for in-house material processing, dye laser pumping for spectroscopic applications and other atmospheric studies in UV region of EM spectrum [1–7]. Due to short emission wavelengths and short excited life of the excimers, threshold values for population inversion are quite high ($10^{14}/cm^3$). These threshold values can only be obtained by depositing high peak electrical power into the gas medium in short time intervals. For switching these high powers, a fast high voltage and high current switch capable of operating at high repetition rate is required. Spark gap and rail gap switches are used for pulsed gas lasers. However, the repetition rate is a limiting factor for these switches. For high repetitive rate and continuous operation, thyratron is an apt device. Nevertheless, these switches are expensive and have limited lifetime. Here, reducing the stress can increase the lifetime of the switches and it is accomplished by decreasing the peak current handling. Furthermore, it allows the generation of longer high voltage pulses, thereby the operational lifetime of the switch is expected to be improved by an order. These longer duration high voltage pulses have to be compressed to ∼100 ns before applying to laser head. Thyratron-based high voltage pulser incorporated with carefully designed magnetic pulse compression (MPC) stage can accomplish this requirement besides MPC permitting thyratron to handle slow raising voltage/current. Spatially uniform pre-ionization of the gas medium is an essential requirement prior to the application of main discharge voltage for ensuring uniform glow discharge. For stable output energy, arc/streamer free glow discharge is primarily required [8–11].

Here, in this paper, a simple, compact, rugged and reliable UV pre-ionized XeCl laser capable of generating a laser output energy of about 120 mJ at a repetition rate of 100 Hz is reported. Uniform UV pre-ionization has been achieved by ensuring evenly distributed current in sparks generated all along the length of the electrode. The spatial profile of the laser output has been measured and its 3D beam profiles show completely filled flat-top profile which is very difficult to generate and measure in case of excimer lasers. Uniformly filled flat top of the XeCl beam is desirable for various material processing applications [12–14]. SEM images of the focussed spot/hole on metal targets are also presented and these images show high pointing stability.

2. Experimental set-up and results

The excimer laser system demonstrated here mainly consists of laser head, gas circulation and cooling unit, single-stage MPC-based HV pulse forming network and high voltage power supply. The laser subassemblies are rigidly mounted inside the compatible laser chamber made up of aluminum alloy with high vacuum and high pressure integrity. For efficient and stable operation of pulsed excimer laser, a compatible laser head is designed and incorporated in the laser system (see figure 1).

The laser head consists of a pair of main discharge electrodes and pre-ionizer assembly. One of the electrodes (HV) is semicylindrical whereas ground electrode is Chang-profiled. The high voltage electrode with in-built pre-ionizer is mounted on a UV non-degradable and HCl compatible high voltage insulator block. This arrangement results in a discharge volume of 1 cm × 2 cm × 50 cm. The pre-ionizer is based on UV spark produced between the tip of a HV pin and electrode. About 50 such pins are inserted in the electrode with the required insulation between the electrode and the pin. For uniform distribution of UV pre-ionization, the pins have been placed all along the electrode on both sides. Each pin is ballasted by a suitable inductor (∼20 nH) to ensure uniform flow of current through all sparks. This arrangement and location of spark pins are staggered on both sides of the high voltage electrode for obtaining spatially uniform pre-ionization throughout the discharge volume [15–18].

Discharge pumped excitation scheme has been chosen for providing fast excitation to achieve glow discharge required for excimer lasers. The schematic of the excitation circuit is shown in figure 2. The excitation circuit primarily consists of a high-voltage power supply, a thyratron as a controllable high voltage switch, main energy storage capacitors, magnetic compression stage and peaking capacitors. The primary capacitor C is a bank of capacitors with a total capacitance of 50 nF. Similarly, Cs is a capacitor bank with 40 nF capacitance. The saturable inductor Ls is made up of Ni–Zn ferrite toroidal cores of dimensions OD = 15 cm, ID = 10 cm and 1.5 cm thickness. Each toroidal core has an effective core cross-section of 15 cm^2, magnetic volume of 29 cm^3 and magnetic path length of about 40 cm. Ls and Cs together make the single stage of MPC. MPC prevents current reversal in the pulsed power circuit and permits optimum adaptation of the thyratron switch in other high voltage components. This results in an increase in lifetime of the most expensive components of the laser–thyratron by more than one order of magnitude. The peaking capacitor Cp consisting of doorknob capacitors (each 2 nF) giving a capacitance of 30 nF has been placed very close to the discharge electrodes. E2V make CX 3608 thyratron has been used as discharge switch for the high repetition rate XeCl laser. With a view to keep minimum loop inductance required for achieving fast rising voltage and current pulses for these particular lasers, a compact discharge current loop has been made. The gas replacement between electrodes between successive discharge pulses at a rep-rate of ∼150 Hz is ensured by the uniform flow provided along the electrodes by magnetically coupled tangential blower. The gas flow was measured by a tachometer mounted on a translational

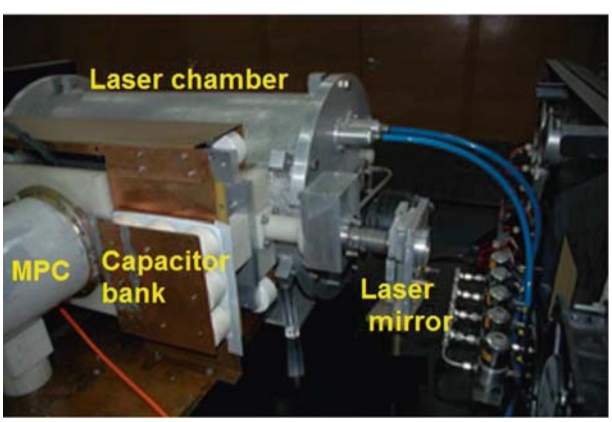

Figure 1. Repetitively pulsed XeCl excimer laser system with single-stage MPC.

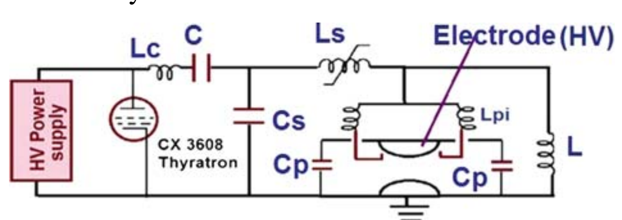

Figure 2. Single-stage MPC high voltage pulser for XeCl excimer laser.

Wilson seal and inserted into the laser head along the electrodes.

The measurement of gas flow between the electrodes was carried out at various speeds of the driver motor up to 1650 rpm and its performance characteristics are shown in figure 3. The gas flow rate of 4 m/s, results in a clearance ratio of 4 for 100 Hz operation. Besides, uniform flow between the electrodes along their length is an essential requirement, particularly for the excimer laser in which glow discharge has to be created and maintained at 2.5 bar operating pressure. Measurement of gas flow is carried out in the discharge volume along the length of the electrodes and the results are depicted in figure 4. It is clearly seen from the figure that gas flow variations are within 1.5%. Precision needle and shut-off valves were used for preparing optimized gas mixture inside the laser. The laser head has quartz windows at both ends of the cavity and the optical cavity is formed by a flat total reflecting mirror and a quartz window separated by 120 cm. All the electrical waveforms were recorded using Lecroy 9350 A (500 MHz, 1 GS/s) oscilloscope, voltage pulses were measured by Lecroy high-voltage probes (PHV4-3033) and current was measured by Tektronix current probe (P 6012 A) with Tektronix current transformer (CT-4).

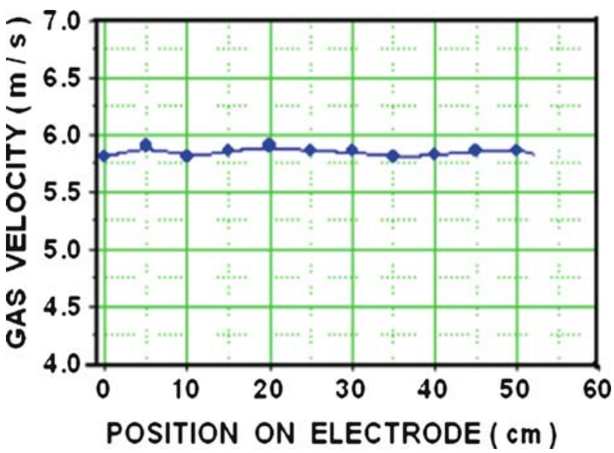

Figure 3. Gas flow velocity between the electrodes vs. position of electrode.

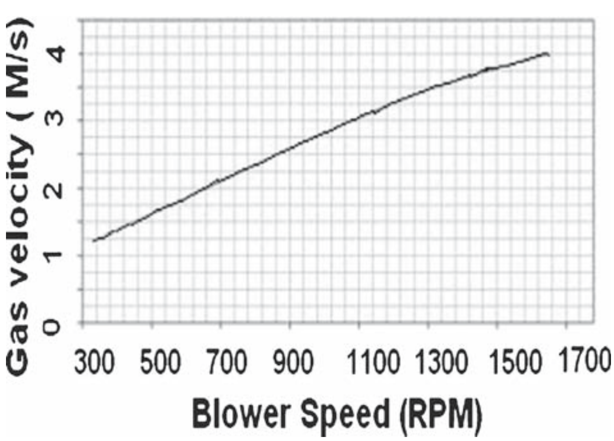

Figure 4. Velocity of the gas between the laser electrodes vs. blower speed.

A capacitor charging power supply charges the primary capacitance C (40 nF) to 28 kV in a time scale of about 1 ms defined by Lc, L and C. On switching the thyratron, the C charges Cs (40 nF) through Lc to ∼28 kV in 260 ns. Here, Lc has been chosen such that the primary capacitor C charges the MPC stage capacitor Cs in a relatively longer time duration of ∼260 ns compared to 100 ns without MPC. Here, due to longer charging time, $\mathrm{d}I/\mathrm{d}t$ on the thyratron is low in this particular case, thereby reducing stress on the thyratron. Simultaneously, HV pulse appears across the saturable inductor (Ls) of the MPC stage and it gets saturated as it was designed to saturate at $V = 28$ kV and $t = 260$ ns. On saturation of Ls, the capacitor Cs discharges and the capacitor ($C_P = 40$ nF) of the laser head gets charged by breaking the gap between the HV electrode and the pre-ionizer pin in 100 ns. Here, the compression factor is 2.6 and the peak current handled by thyratron with single stage MPC has been reduced to ∼8 kA from ∼12 kA without MPC stage. In order to achieve 100 ns (time to increase the voltage of the laser head) as required by these pulsed lasers, designing the MPC stage is very critical and loop inductance including saturable inductance has to be kept as low as possible. A single-turn saturable inductor has been designed and incorporated in the circuit. The housing of the ferrite cores, in turn, acts as a single turn for saturable inductor. Moreover, it acts as low impedance transformer line (coaxial current return path) to keep the inductance as low as possible. The schematic of the single-stage MPC with Ni–Zn toroidal cores is shown

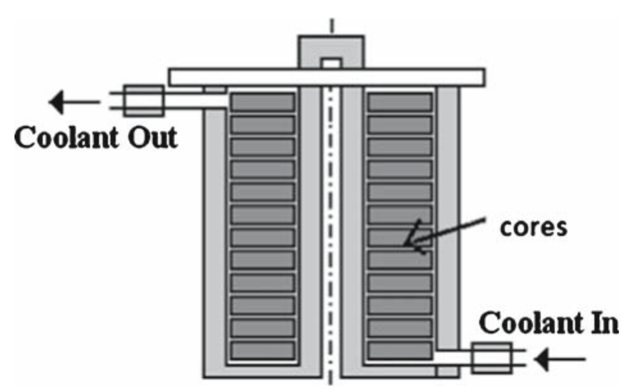

Figure 5. Schematic of the single-stage MPC with Ni–Zn toroidal cores.

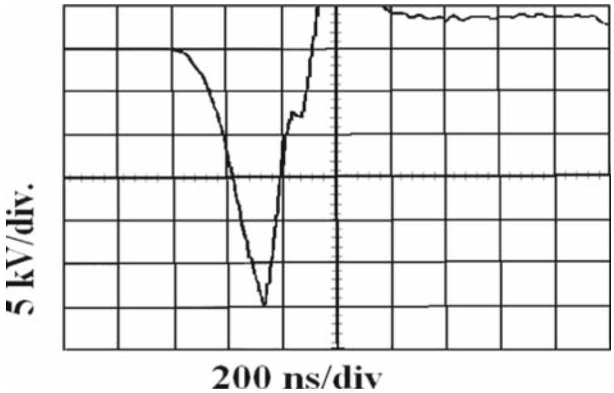

Figure 6. Charging voltage pulse of Cs (voltage rise time = ∼260 ns).

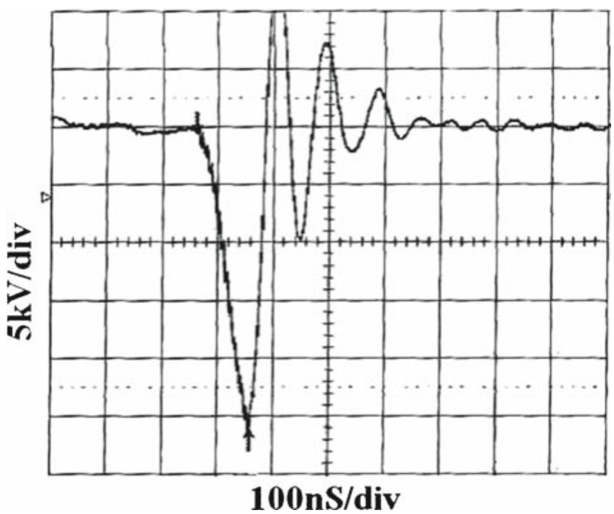

Figure 7. Discharge voltage pulse across the laser head (voltage rise time = ∼100 ns).

in figure 5. The resultant voltage pulses across the Cs and the laser head are shown in figures 6 and 7 respectively. To maximize energy transfer of the MPC, C and Cs of the same value have been chosen. The optimized concentration of the constituents of the gas mixture is 0.15% HCl, 3% xenon and 96.85% neon at a total chamber pressure of 2500 mbar. The discharge breakdown voltage was found to be 26 kV and this resulted in producing optical pulses of 120 mJ energy at a repetition rate of 100 Hz. The typical discharge voltage pulse and the corresponding temporal profile of the XeCl excimer laser pulse measured with Hamamastu make fast photodiode, are shown in figure 8. The performance characteristics of the output energy of the laser with respect to the repetition rate is shown in figure 9. Here, the fall in energy of the laser beyond the repetition rate of 100 Hz is due to reduced clearance ratio of the gas mixture between the electrodes.

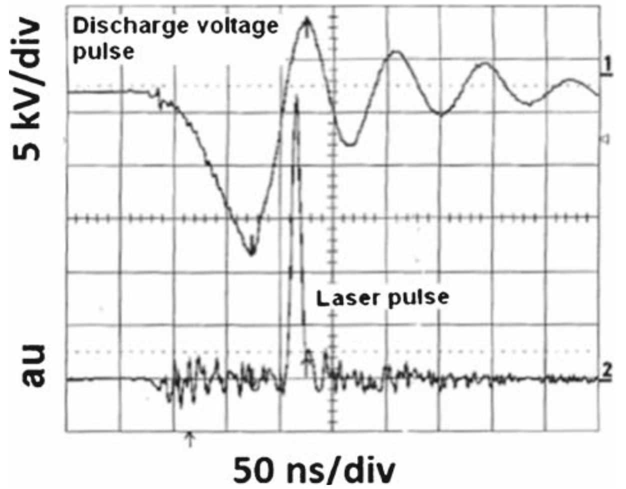

Figure 8. Typical discharge voltage pulse and the corresponding laser pulse.

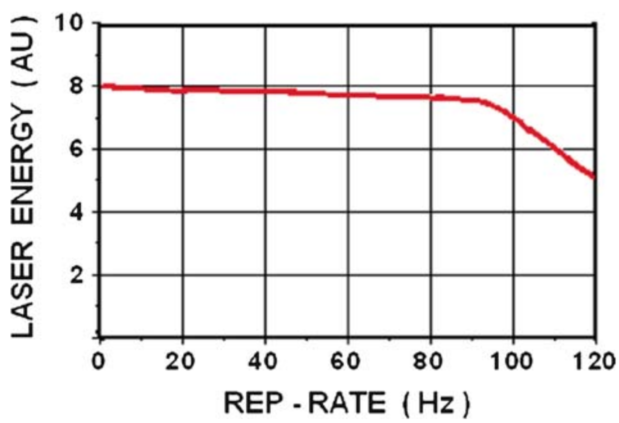

Figure 9. Performance characteristics of laser energy at different repetition rates.

3. Excimer laser profile recording

The beam profile recording of UV excimer laser is a challenging task. The commercial laser beam profilers in the UV region are costly and often unavailable to the user. The high beam intensity is attenuated to the acceptable level before feeding to the commercial beam profiler. We devised an in-house method of recording/estimating the beam profile using semitransparent screens/papers and the SLR digital camera commonly available in the market for normal social photography. The spatial profile of the repetitively pulsed XeCl excimer laser, captured by SLR digital camera D-70 Nikon, has been recorded on semitransparent screen, and analysed by commercial software. The advantage of this technique is that the semitransparent screens can be calibrated and used as per the choice. The digital camera can be used in zoom position or in the autofocus mode as per the user settings and provide greater flexibility in the approach. The spatial profile beam was recorded from the back of semitransparent fluorescent screen (flat plate) using digital camera and was analysed subsequently using relevant software. Here, the beam cross-section was found to be completely filled with flat-top intensity profile. This was also confirmed at various reduced beam intensities using beam attenuator and the obtained profiles were found to be completely filled flat-top ones. These experiments have been carried out with a view of avoiding the effect of saturation and features of hot spots have not been observed in the beam. The 2D view pertinent to the recorded beam profile is depicted in figure 10.

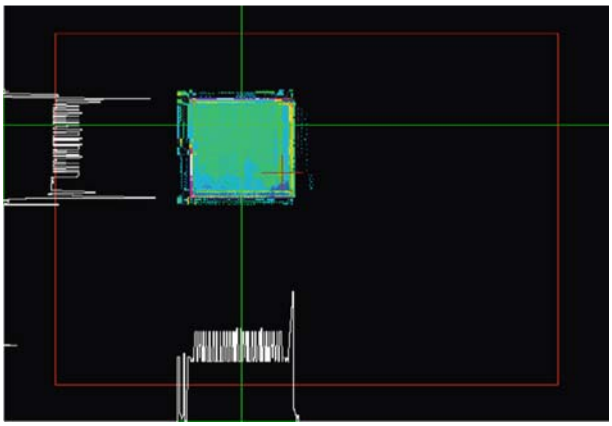

Figure 10. 2D beam profiles (flat-top).

4. Excimer laser material processing applications for generating microholes in metal sheets

Clean micromachining is also demonstrated using XeCl laser with prism resonator cavity. The laser equipped with prism resonator configuration has been used for micromachining applications. The laser beam was focussed using a plano-convex lens of 100 cm focal length, placed close to the exit window of the laser. The laser beam was focussed on copper and aluminum thin plates placed at the focal plane of the plano-convex lens. With these beam parameters, the microhole has been created on a 0.2 mm thick copper sheet and the captured SEM image of the hole depicted in figure 11 shows that the created hole is clean and sharp.

5. Conclusion

Performance characteristics of an excimer laser with single-stage magnetic pulse compression suitable for

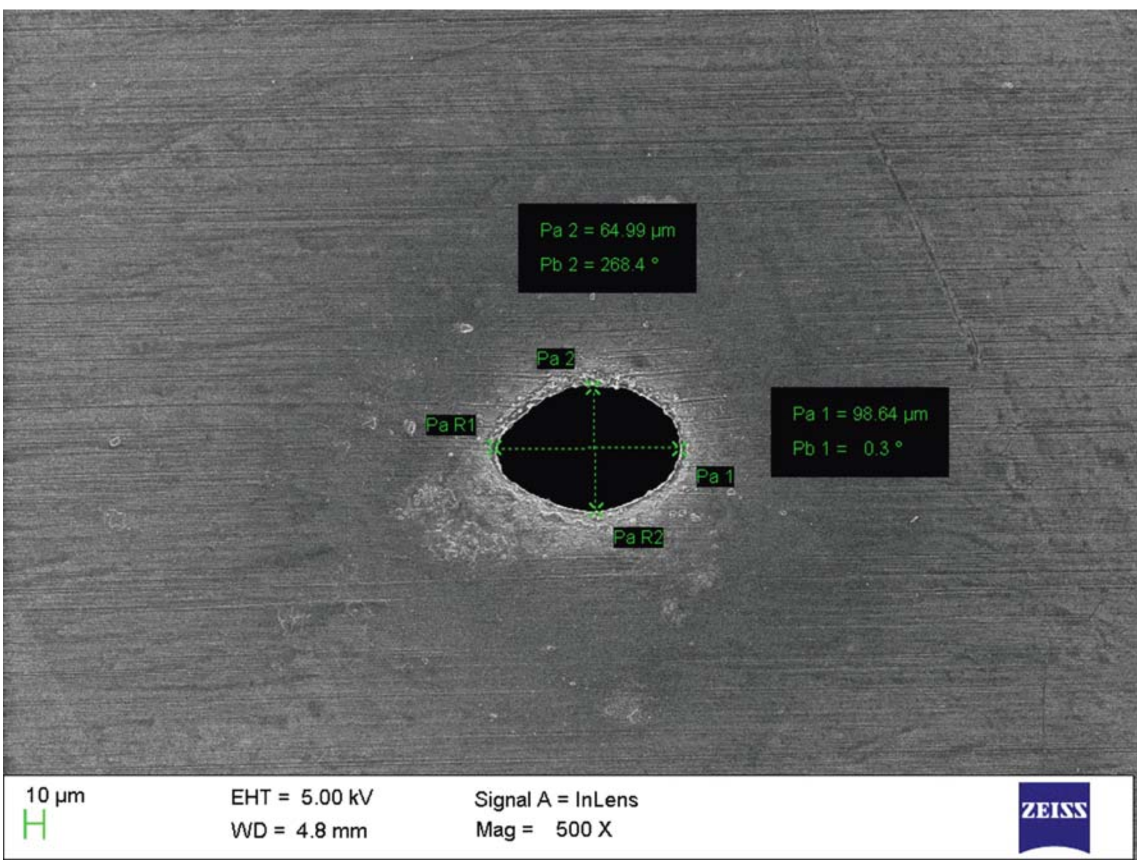

Figure 11. SEM image of the microhole generated with XeCl laser beam on a 0.2 mm thick copper sheet.

material processing applications is presented here. Thyratron-based HV exciter with C–C energy transfer circuit has been used for this laser. With a view to reduce stress on the thyratron, a single-stage magnetic pulse compression has been incorporated in the circuit. Low inductance of the laser head and uniform and intense pre-ionization are the main features of the electric circuit used in the laser. A 250 ns rise time voltage pulse was compressed to 100 ns duration with a single-stage magnetic pulse compressor using Ni–Zn ferrite cores with a compression factor of 2.5. The flat-top profiles are demonstrated by establishing uniform homogeneous gas discharge in the laser. Here, demonstration of clean micromachining shows the high pointing stability of the laser.

Acknowledgements

The authors wish to thank Shri Bijendra Singh, Laser Materials Processing Division, for the technical discussions, constant support and encouragement in this work.

References

[1] Ying-Tung Chen, Kris Naessens, Roel Bates, Yunn-Shiuan Liao and A A Tseng, *Opt. Rev.* **12**, 427 (2005)
[2] Xiang Zhang, Costas P Grigoropoulos, Douglas J Krajnovich and Andrew C Tam, *IEEE Trans. Compon. Packag. Manuf. Technol. C* **19**, 201 (1996)
[3] R R Krueger, Y S Rabinowitz and P S Binder, *J. Refract. Surg.* **26**, 749 (2010)
[4] T Uhrmann and R Delmdahl, *Solid State Technol.* **56**, 18 (2013)
[5] R Paetzel, B Turk, J Brune, S Govorkov and F Simon, *Phys. Status Solidi C* **5**, 3215 (2008)
[6] L Herbst, H Lindner, M Heglin and T Hoult, *Indust. Laser Solutions* **19**, 13 (2004)
[7] R Delmdahl and R J Patzel, *Phys. D*: *Appl. Phys.* **47**, 0340047 (2014)
[8] S Szatmari, J Janicsko and J Bohus, *Rev. Sci. Instrum.* **78**, 0361081 (2007)
[9] J I Levatter and S C Lin, *J. Appl. Phys.* **51**, 210 (1980)
[10] R S Taylor, A J Alcock and K E Leopold, *Opt. Lett.* **5**, 216 (1980)
[11] L Fenestra, O B Hoekstra, P J M Peters and W J Witteman, *Appl. Phys. B* **70**, 231 (2000)
[12] P Kossowsky, *Optical resonators – Science and engineering* (Springer, Pittsburgh, 1998)
[13] N Hodgson and H Weber, *Laser resonators and beam propagation, Fundamentals, advanced concepts and applications* (Springer, New York, 2005) Vol. 2
[14] T Kajava, A Hakola, H Elfstrom, J Simonen, P Paakkonen and J Turenne, *Opt. Commun.* **68**, 289 (2006)
[15] M Geiger, S Roth and W Becker, *SPIE* **404**, 200 (1997)
[16] K Miyazaki, T Hasama, K Yamada, T Fukatsu, T Eura and T J Sato, *Appl. Phys.* **60**, 2721 (1986)
[17] M Hiramastsu and T Goto, *Rev. Sci. Instrum.* **57**, 534 (1986)
[18] D Basting and G Marowsky, *Excimer laser technology* (Springer, Gottingen, 2005)