



Original research article

Precise measurement for beam pointing stability of high power repetition rate TEA CO₂ laserKuo Zhang ^{a,b,*}, Fei Chen ^{a,b}, Guilong Yang ^{a,b}, Dianjun Li ^{a,b}, Jin Guo ^{a,b}^a State Key Laboratory of Laser Interaction with Matter, Changchun Institute of Optic, Fine Mechanic and Physics, Chinese Academy of Science, Changchun 130033, China^b Innovation Laboratory of Electro-Optical Countermeasures Technology, Changchun Institute of Optic, Fine Mechanic and Physics, Chinese Academy of Science, Changchun 130033, China

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ABSTRACT

High power repetition rate TEA CO₂ laser emits high power and high pulse energy far-infrared laser, the laser spot and beam pointing stability is difficult to measure with commercial detectors directly. In this paper, a method is proposed to measure the beam pointing stability of high power repetition rate TEA CO₂ laser. A laser with average power of 10 kW and repetition rate of 400 Hz is adopted as sample for measurement. An experimental device is optimally design to attenuate laser power and measure the laser spot. Beam pointing stability can be calculated from the measured result and the aberration caused by the experimental measurement is discussed. A correction algorithm based on the laser parameters is proposed and the beam pointing stability of this TEA CO₂ laser can be calculated as 39.93 μrad and 145.53 μrad in x direction and y direction respectively.

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1. Introduction

High power repetition rate TEA CO₂ laser (transversely excited atmosphere CO₂ laser) can generate high average power, high pulse energy far-infrared laser, which has numerous applications in scientific research, medical treatment and industrial process [1–9]. The wavelength of CO₂ laser is in the range of 8 μm–12 μm of atmosphere transmission region, the energy attenuation of laser is small in far distance transmission [10,11]. Beam pointing stability is one of the important parameters for determination the property and quality of high power laser beam when it is used in far distance transmission. The precise measurement of beam pointing stability is essential for evaluating the performance of the high power repetition rate TEA CO₂ laser [12,13]. Beam pointing stability can be calculated from the laser spot. Plexiglass is used to sample the high power laser spot [14], the laser spot sampled on plexiglass is affected by the laser power density and irradiating time. The spot edge sampled on plexiglass is difficult to extract, the centroid position and spot size cannot be calculated accurately. Laser beam detectors are commonly adopted to record the laser spot, they are not suitable for high power laser due to the lower damage threshold. Hence splitting laser to a suitable power is essential for high power laser measurement. Maestle et al. [15] stated a measuring method for continuous wave CO₂ laser with power of 525 W, a reflection grating (including water cooling) was used as beam splitter to provide two samples of the laser beam with the power of 1.5 W and 1.8 W, then Hartmann sensor and

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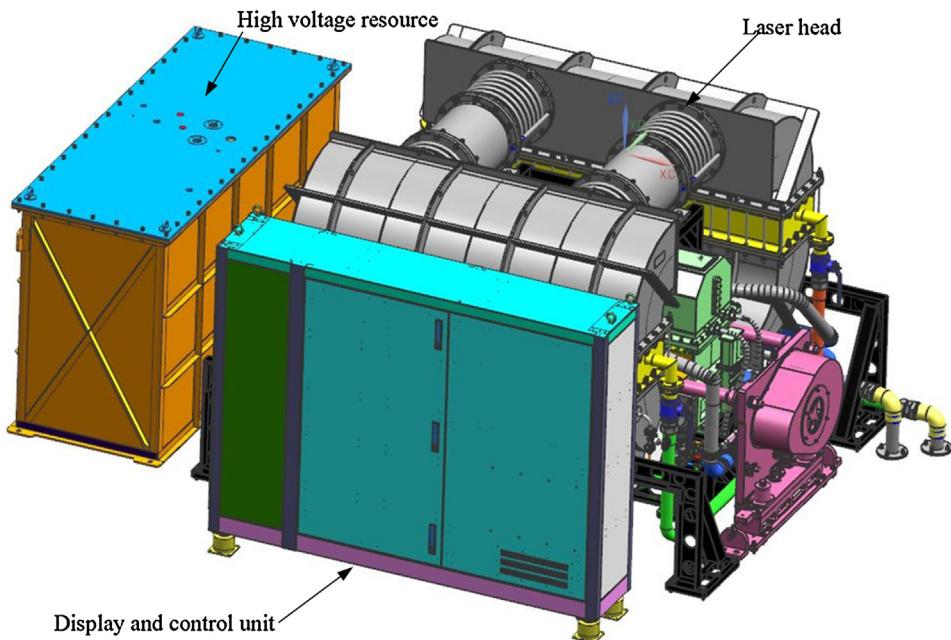


Fig. 1. the sketch of high power repetition rate TEA CO₂ laser.

Pyrocam detector were used to measure the beam pointing stability. The detecting results of both detectors were compared to show a good agreement within a few μrad . However, the average power of repetition rate TEA CO₂ laser is over 10 kW, the peak power and pulse energy is too high, therefore splitting laser is difficult, little research focus on the measurement of the laser spot and beam pointing stability in high power repetition rate TEA CO₂ laser.

In this paper, the beam pointing stability of a high power repetition rate TEA CO₂ laser is studied. An experimental device is established to attenuate the laser power and compress the spot size for measurement by laser beam detector. Experimental results and theoretical results are compared and analyzed, the aberration caused by the deviation between theoretical focal plane and detecting plane is corrected with laser spot. Then, the measured beam pointing stability is transferred into focal plane and the actual beam pointing stability is calculated.

2. High power repetition rate TEA CO₂ laser

The high power repetition rate TEA CO₂ laser for measurement is sketchily shown in Fig. 1. The laser is consisted of three main parts. The laser head is equipped with an optical resonator, a discharge cavity, a heat exchange device, a pressure control device, a rotary spark switch and a high voltage pulsed trigger. This laser employs a plane-concave resonator. Two symmetrical Chang-electrodes are installed in the discharge cavity. The heat exchange device takes the heat generated in the laser working process away. The pressure control device is used to control the working gas pressure. Rotary spark switch and high voltage pulsed trigger is used to control the generation of repetition rate laser. Ultraviolet preionized technique is adopted for uniform glow discharge. Laser operation is controlled by a display and control unit. The whole equipment is power by high voltage resource.

Key parameters of this high power repetition rate TEA CO₂ laser are listed as follow: laser wavelength is 10.59 μm , average output power is 10 kW, energy of single laser pulse is near 25 J. The operation repetition rate is set to 400 Hz. The laser spot at the output window was recorded on the thermosensitive paper, as shown in Fig. 2. The spot size (half width of spot) is $W_{0x} = 22.7$ mm and $W_{0y} = 20.9$ mm. The laser pulse is measured by an infrared HgCdTe detector connected with an oscilloscope. The pulse laser waveform of TEA CO₂ laser is shown in Fig. 3, the full wave at half maximum (FWHM) of peak pulse is near 100 ns. Therefore, the peak power can be calculated as 250 Megawatt. The TEA CO₂ laser with the characteristic of high power and narrow pulse width can easily damage the detector, which makes the laser spot and pointing stability difficult to measure.

3. Experimental measurement setup

An experimental measurement device is proposed to measure the beam pointing stability of high power repetition rate TEA CO₂ laser, (as shown in Fig. 4). The device is consisted of a laser attenuation and compression unit and a beam measurement unit. The laser beam of high power repetition rate TEA CO₂ laser is converted to a suitable value through the laser attenuation and compression unit, and then it can be measured by beam measurement unit. To reduce the influence

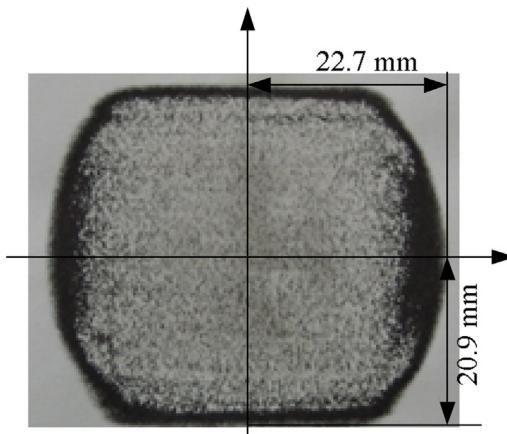


Fig. 2. Laser spot at the output window recorded on the thermosensitive paper.

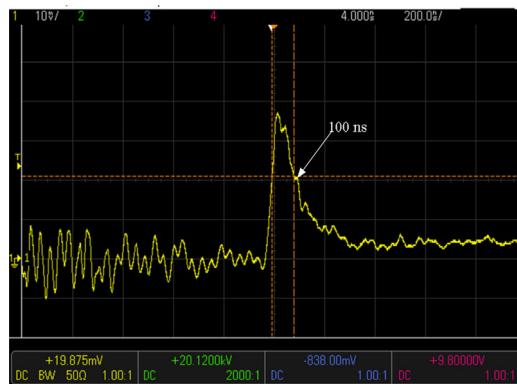


Fig. 3. Pulse laser waveform.

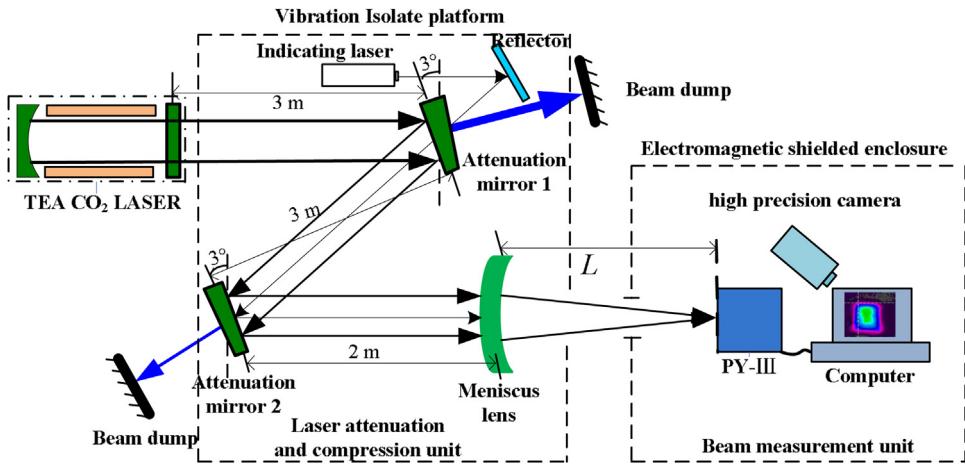


Fig. 4. Experimental setup for beam pointing stability measurement.

of vibration generated by the axial-flow fans in TEA CO₂ laser itself, the laser attenuation and compression unit is mounted on a vibration isolation platform. Electromagnetic interference generated by high voltage discharge during laser operation process has a huge influence on measurement, the measurement device and computer communication will be disturbed by electromagnetic interference, therefore the beam measurement unit is located in an electromagnetic shielded enclosure. There is a small window in the wall of the enclosure to let the measured laser pass through. Then the laser is measured by the detector and the laser spot and beam parameters can be shown on the interface of computer.

The laser attenuation and compression unit is composed of two pieces of wedge mirrors and one piece of meniscus lens. The wedge mirrors are adopted to eliminate the interference of reflected laser from back side of mirror. Both of the wedge mirrors are made of ZnSe substrate with 10.59 μm antireflection coating deposited on laser incident surface. The high power of TEA CO₂ laser will cause thermal lens effect, therefore the reflected laser is used for measurement. The transmittance of the wedge mirrors is 99%, only 1% laser is reflected to the experimental measurement device. The average output power has been attenuated 10⁴ times after the laser passes through the wedge mirrors.

For precision measurement, the reflected beam from the reflecting surface of wedge mirrors must be separated from the incident laser. The laser spot size is 45.4 mm and 41.8 mm in x direction and y direction respectively, the divergence angles are measured as 6.63 mrad and 6.03 mrad in x direction and y direction respectively [16]. The spot size is theoretically calculated as 85.18 mm and 77.98 mm when the laser reaches meniscus lens. There is an angle between the incident laser and reflected laser to separate them. The spot size projected on the wedge mirror is related to the angle, the projection spot should be completely within the scope of the wedge mirrors. The larger the angle is, the farther the incident laser and reflected laser forms, but the higher the manufacturing cost of wedge mirrors is. Therefore it is reasonable to assume that the incident beam and reflected beam is 200 mm apart at the distance of 3 m from the wedge mirror. Hence, the incidence angle of laser can be calculated as 3°, the size of wedge mirror can be determined as 100 mm × 100 mm.

The meniscus lens is made of the ZnSe material as well, theoretical focal length *f* of the meniscus lens can be calculated as:

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} - \frac{1}{R_2} + \frac{t(n - 1)}{nR_1R_2}\right) \quad (1)$$

Where *n* = 2.436 is material's index of refraction, *t* = 14.26 mm is center thickness and *R*₁ and *R*₂ is radius of curvature, *R*₁ = 218.3 mm and *R*₂ = 525.4 mm, then the theoretical focal length *f* of this meniscus lens can be calculated as 259.22 mm. For the divergence angle of this laser is 6.63 mrad and 6.03 mrad in x direction and y direction respectively, the spot size at meniscus lens is 98.44 mm and 89.64 mm. The spot size is much larger than the incident window of laser beam detectors, therefore the laser beam should be focused through the meniscus lens for measurement.

Pyrocam-III (Ophir-Spiricon inc., short for PY-III) is adopted as the beam position detector, active detecting area is 12.4 mm × 12.4 mm. The damage threshold of the detector is defined in power and energy aspects. Damage threshold of power is 2 W over the entire internal detecting array and damage threshold of energy is 20 mJ/cm² for ns pulse width laser. The average power of the attenuated laser is 1 W, which is below the power damage threshold of PY-III. The energy density of laser beam is related with the pulse energy and spot size. The pulse energy is attenuated to 2.5 mJ. According to the relationship of energy density, if the energy density is lower than the damage threshold of the detector, the laser spot size must be greater than 0.125 cm². The edge length of spot should be larger than 4 mm in x and y direction for safety.

He-Ne laser is used as indicating laser to adjust the position of the wedge mirrors, meniscus lens and detector to coaxial optical system before measurement. The distance between the wedge mirrors and meniscus lens along optical axis can be determined with ruler. The spot size is related with the position of the detector along the optical axis. As we discussed above, the edge length of spot should be greater than 4 mm in x and y direction to meet the demand of energy density. A thermosensitive paper is placed in front of the detector window to record the spot size. The thermosensitive paper is moved back and forward along the optical axis to find a location where the spot size is suitable for measurement and the energy density of laser spot is below the damage threshold. Then the distance *L* between the meniscus lens and detector is determined.

The distance between the output window of TEA CO₂ laser and the meniscus lens is 8 m. The value of *L* is determined in the measuring process, which will be different from the theoretical focal length of the meniscus lens. Aberration between *L* and focal length will be determined and the influence of the aberration will be discussed in the following section.

4. Experimental result and analysis

The measured beam spot pattern is shown in Fig. 5, and it describes the power density distribution of the laser spot. The beam centroid position is second moment of power density distribution. The software is integrated with the beam centroid position algorithm and the beam centroid position and spot width in x direction and y direction can be calculated by the internal software.

In order to improve the measurement accuracy, the experiment data must be obtained in one laser operating circle. The repetition rate of laser is 400 Hz, the sample frequency of PY-III detector is 50 Hz, the probability of laser pulse acquisition by the detector is reduced. The laser operating circle must be prolonged to increase the probability. Since there is no memory in PY-III detector, a high precision camera is used to record the spot pattern and parameters shown on software interface, the valid information (The beam centroid position and the laser spot size) for beam pointing stability calculation can be extracted from the camera record, as list in Table 1.

Fig. 6 shows the distribution of the laser centroid position. X axial and Y axial denote the x coordinate and y coordinate of the centroid position respectively. All the points locate in the circle with the diameter of 90.6 μm, which represents the variation range of the centroid position. The variation along y coordinate is much larger than the variation of x coordinate, which means the centroid position fluctuation of y coordinate is large.

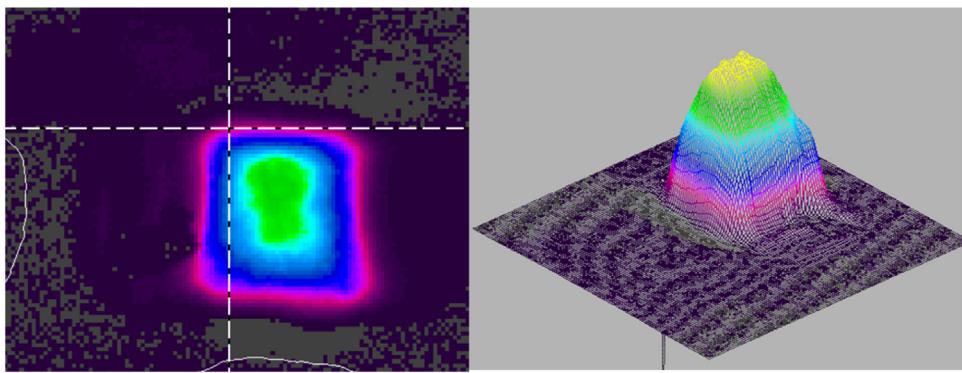


Fig. 5. 2D and 3D laser spot distribution.

Table 1

Centroid position and laser spot size measured by the detector.

	X.c (mm)	Y.c (mm)	X_width (mm)	Y_width (mm)
1	7.48	8.36	4.59	4.80
2	7.48	8.35	4.78	4.84
3	7.48	8.33	4.70	4.81
4	7.49	8.3	4.70	4.88
5	7.48	8.32	4.74	4.87
6	7.49	8.35	4.67	4.89
7	7.48	8.30	4.66	4.82
8	7.49	8.33	4.73	4.81
9	7.49	8.31	4.69	4.85
10	7.49	8.33	4.62	4.82
11	7.48	8.38	4.70	4.84
12	7.48	8.34	4.70	4.83
13	7.49	8.29	4.79	4.90
14	7.48	8.36	4.66	4.84
15	7.48	8.36	4.69	4.8
16	7.48	8.35	4.73	4.86
17	7.49	8.32	4.79	4.83

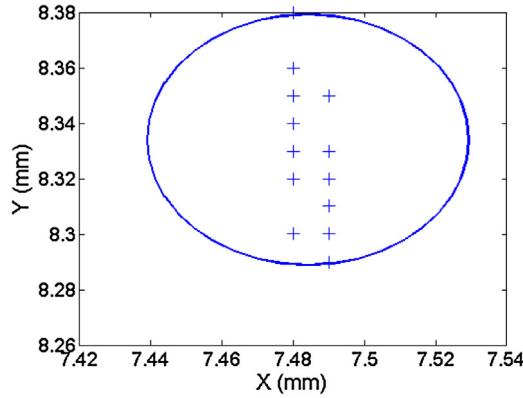


Fig. 6. Distribution of the laser centroid position.

According to the model for beam pointing stability [17], the detector must be put at the focal point. Δ_x denotes the laser beam positional fluctuation, Δ_x is defined as two times of the standard deviation of the measured centroid position distribution at focal plane:

$$\Delta_x = 2 \sqrt{\frac{(x_i - \bar{x})^2}{(n - 1)}} \quad (2)$$

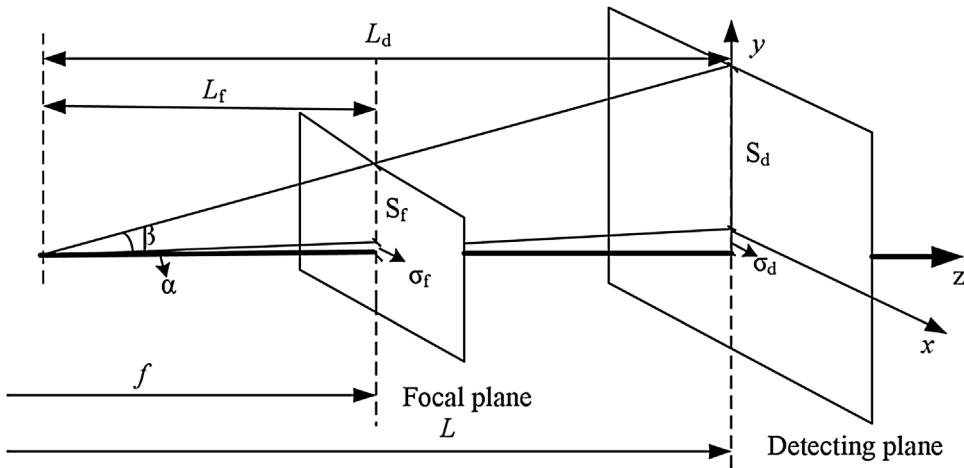


Fig. 7. Distribution of the laser beam parameters between theoretical focal plane and detecting plane.

Where x_i denotes the measured value of centroid position in x direction, and \bar{x} denotes the mean value of the centroid position in x direction. The beam pointing stability can be theoretically calculated as:

$$\Delta\alpha_x = \frac{\Delta x}{f} \quad (3)$$

Where f is the focal length of the meniscus lens, it is determined by the structure and material of the meniscus lens. Here, the focal length is calculated as 259.22 mm.

As discussed in experiment measurement setup section, the position of PY-III detector may not be installed at the right place of the focal plane. The place of the detector is related with the spot size recorded on thermosensitive paper. The distance L between the detector and the meniscus lens is usually larger than the focal length f . Therefore, a correction is made to the model and the influence of deviation between L and f will be considered.

Fig. 7 illustrates the relationship between parameters on detecting plane and parameters on theoretical focal plane. The theoretical focal plane was moved forward along z axial for clear expression. The laser beam propagates directly, as the distance increasing, the beam size and centroid position will change in a certain relationship. The change of beam size is due to the laser divergence action, the change of centroid position is due to the laser pointing fluctuation. In order to obtain accurate values of beam pointing stability, the deviation between detecting plane and theoretical focal plane must be considered, the measured beam position fluctuation must be transferred into theoretical focal plane for further calculation.

The laser spot size S_d and the beam position fluctuation σ_d at the detecting plane can be obtained from the data measured by PY-III detector. The mean value of S_d is 4.7024 mm and 4.846 mm, the beam position fluctuation σ_d is 0.0412 mm and 0.177 mm in x direction and y direction respectively.

S_f denotes the laser spot size at theoretical focal plane. For the effects of diffraction and spherical aberration, the laser spot at focal point can be calculated by Eq. (4).

$$S_f = \frac{4\lambda M^2 f}{\pi D \times 10^{-3}} + \frac{kD^3}{f^2} \quad (4)$$

Where $\lambda = 10.59 \mu\text{m}$ is laser wavelength, the input laser diameter at the meniscus lens is $D_x = 93.4 \text{ mm}$ and $D_y = 89.8 \text{ mm}$. M^2 factor of this TEA CO₂ laser is 25.5 and 21.3 in x direction and y direction, respectively, k is an index of refraction function, for ZnSe meniscus lens, $k = 0.0187$. Then the spot size S_f can be calculated as 1.1819 mm and 1.0314 mm in x direction and y direction respectively.

σ_f denotes the beam position fluctuation at the theoretical focal position, which is located at the same plane with S_f . Laser propagation is in accordance with the geometrical optics law. The relationship between theoretical focal plane and detecting plane can be built. The ratio of beam position fluctuation σ_f/σ_d equals to the ratio of L_f/L_d , the deviation between L_f and L_d is in coordinate with the deviation of f and L . The accurate value of parameters, L_f , L_d and L are difficult to determine in the detecting process, but the ratio of L_f/L_d equals to the ratio of S_f/S_d , hence the relationship between beam position fluctuation and laser spot size can be expressed as:

$$\sigma_f/\sigma_d = S_f/S_d \quad (5)$$

Consequently, the measured beam position fluctuation is translated into focal plane and the corresponding value σ_f at focal plane can be obtained. Then the value of laser pointing stability can be calculated as 39.93 μrad and 145.53 μrad in x direction and y direction respectively.

5. Conclusion

Study on beam pointing stability of high power repetition rate TEA CO₂ laser has been carried out in this paper. The laser spot and beam pointing stability of the laser with average power of 10 kW and single pulse energy of 25 J was experimentally measured. An experimental setup is established and laser spot can be obtain. The aberration between theoretical analysis and experimental measurement was discussed. A correction algorithm based on the relationship between theoretically calculated spot and actually measured spot was proposed to correct the aberration. As a result, the accurate beam pointing stability can be calculated as 39.93 μrad and 145.53 μrad in x direction and y direction respectively.

References

- [1] M.J. Torkamany, M. Kavian, M. Zand, Experimental study of sealed off operation of a high repetition rate TEA CO₂ laser, *Laser Phys. Lett.* 10 (2006) 480–484.
- [2] M. Zand, S.A. Naeimi, A 300 Hz TEA CO₂ laser, *J. Russ. Laser Res.* 31 (2010) 98–100.
- [3] H. Kariminezhad, P. Parvin, F. Borna, A. Bavali, SF6 leak detection of high-voltage installations using TEA-CO₂ laser based DIAL, *Opti. Laser Eng.* 48 (2010) 491–499.
- [4] H.C. Tse, H.C. Man, T.M. Yue, Effect of magnetic field on plasma control during CO₂ laser, *Opt. Laser Technol.* 31 (1999) 363–368.
- [5] J.J. Xie, Q.K. Pan, R.H. Guo, P. Zhang, D.J. Li, G.L. Yang, C.S. Zhang, J. Guo, Dynamical analysis of acousto-optically Q-switched CO₂ laser, *Opt. Laser Eng.* 50 (2012) 159–164.
- [6] M. Momcilovic, M. Trtica, J. Ciganovic, J. Savovic, J. Stasic, M. Kuzmannovic, Analysis of copper surface features obtained using TEA CO₂ laser at reduced air pressure, *Appl. Surf. Sci.* 270 (2013) 486–494.
- [7] R.Q. Tan, C.W. Wan, J.L. Qi, S.M. Liu, J.W. Zhou, W.J. Xie, J. Wu, A sequential discharge TEA CO₂ laser with high repetition rate and high output power, *Opt. Laser Technol.* 31 (1999) 393–396.
- [8] G.L. Yang, D.J. Li, J.J. Xie, L.M. Zhang, F. Chen, J. Guo, L.H. Guo, High power repetitive TEA CO₂ pulsed laser, *Laser Phys.* 22 (2012) 1173–1176.
- [9] M. Kumar, A.K. Biswas, P. Bhargav, T. Reghu, S. Sahu, J.S. Pakhare, M.S. Bhagat, L.M. Kuhreja, Theoretical estimation and experimental studies on gas dissociation in TEA CO₂ laser for long term arc free operation, *Opt. Laser Technol.* 52 (2013) 57–64.
- [10] M. Aram, S. Jelvani, M. Nazari, S. Panahibakhsh, Single mode operation of a TEA CO₂ ring laser, *J. Appl. Spectrosc.* 80 (2013) 624–627.
- [11] P.W. Pace, J.M. Cruickshank, A frequency stabilized compact high repetition rate TEA CO₂ laser, *IEEE J. Quantum Electron.* Qe-16 (1980) 937–944.
- [12] P. Kwee, F. Seifert, B. Willke, K. Danzmann, Laser beam quality and pointing measurement with an optical resonator, *Rev. Sci. Instrum.* 78 (2007) 073103.
- [13] H.R. Yang, L. Wu, X.X. Wang, J.F. Shi, G.P. Li, X.J. Evaluation of beam quality for high-power laser, *Proc. SPIE* 682316 (2007).
- [14] H. Peng, D. Wang, X.H. Tang, R.T. Zhong, Q.S. Deng Experimental studies of a plane-cone resonator for high power, transverse-flow CO₂ laser, *Opt. Eng.* 51 (4) (2012) 044204.
- [15] R. Masette, W. Plass, J. Chen, Chr. Hembd-Soellner, A. Giesen, H. Tiziani, H. Hugel, Investigation of beam pointing stability, far field divergence angle and power density distribution of high power CO₂ laser, *SPIE* 2870 (1996) 319–326.
- [16] K. Zhang, J. Lu, G.L. Yang, F. Chen, D.J. Li, C.B. Zheng, J. Guo, Estimation of far-field divergence of high power TEA CO₂ laser (in Chinese), *Infrared Laser Eng.* 44 (2015) 2286–2291.
- [17] SO/DIS 11670 Test methods for laser beam parameters: beam positional stability.