Laser beam quality measurement by micro lens array method

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Abstract

In the traditional laser beam quality measurement, the lens transform method is used to obtain the information of the multi spot, and can only evaluate the beam quality of a continuous or high repetition rate laser, the evaluation speed is slow and the real-time performance is poor. A micro lens array method is proposed, which samples the laser spot only once and obtains all the spot information, the intensity data and phase distribution of the laser beam are determined by reconstructing the laser wave front, then calculates the beam quality parameters of laser beam according to the Wegener method. According to the ISO15367 standard, designs and implements a beam quality measurement system based on micro lens array method, which has the advantages of small size, fast measurement speed and high accuracy. The test shows that the measurement accuracy of the beam quality factor is 5%, Laser beam quality factor, beam width, and beam divergence angle parameter values can be digitized, Intensity and phase distribution of laser beam can be displayed directly, comprehensive evaluation of laser beam quality is realized.

Keywords

Laser beam quality, micro lens array, Wegener distribution, wave front reconstruction.

1. Introduction

At present, Laser technology has been developed rapidly. Laser industry has become a pillar industry of the national economy. Laser related technologies and products are constantly applied to the rapidly changing industrial processes, communications, medical and national defense and other fields, and play an increasingly important role in the national economic development and social progress. The application scope of laser technology is expanding, and the new type of laser is emerging, which make correctly knowing and understanding the spatial characteristics of the laser beam particularly important. Because the contour distribution of the spot shows the full spatial characteristics of the laser beam, and also shows how to efficiently adjust and modify the design of the laser to ensure high quality laser output. If the beam profile is unknown, the laser will be difficult and can't be put into use[1][2].

Laser beam analysis and measurement of beam quality have become one of the hot topics in the field of laser engineering. In laser beam parameter measurement, M2 factor method has many advantages compared to other methods, It can comprehensively describe the laser beam quality from two aspects, the beam divergence angle and the beam width. The traditional M2 factor measurement method uses the lens transformation method, which samples the laser beam in the axial direction, needs executive components. This method has disadvantages such as complex hardware, long measuring time, the test object confined to the continuous laser and high frequency pulse laser [3]. Therefore, based on the study of the ISO 15367 standard, this paper proposes the use of micro lens array integrated CCD sensor for laser spot single sampling and using mode method to reconstruction laser wave-front. On the hardware, the selection and design of the parameters of the array detector are discussed, realizes a pulse laser detecting synchronous signal generator, Finally, a laser beam quality measurement system based on the micro lens array is built.

2. Definition of beam quality factor and detection principle of micro lens array

2.1 Beam quality factor

The academic circles have put forward various kinds of parameters to characterize the beam quality for different applications, such as aggregate spot size, far field divergence angle, and so on. The evaluation of the quality of laser beam with these parameters is one-sided. Beam quality M2 factor is an important index to measure the quality of laser beam. Siegman proposed using M2 factor evaluation of laser beam in the early 90's, and be popularized all over the world. The so-called M2 factor is also known as the diffraction limit factor, which is the ratio of the product of the width and divergence angle of the actual laser beam and the product of the width and divergence angle of the ideal base mode Gauss beam, the definition of the expression is.

$$M^2 = \frac{\omega\theta}{\omega_0\theta_0} = \frac{\pi}{\lambda}\omega\theta \qquad (1)$$

In formula (1), ω is the laser beam's radius, θ is the far-field divergence angle, λ is the wave-length. From formula (1), it can be seen that M2 factor not only reflects the near-field characteristics of laser beam the beam waist, but also reflects the far field characteristics of laser beam divergence angle, so it can comprehensively evaluate the near field and far field characteristics of the laser. M2 factor has become the evaluation standard of laser beam quality recommended by international standardization organization [4][5][6].

2.2 Principle of M2 factor detection by micro lens array method

M2 factor can be detected by the micro lens array method. The principle block diagram of which is as shown in Figure 1. The laser beam emitted by the tested product is sampled by the micro lens array, and it is split into many small areas [7],[8]. A number of sub spot images in the CCD sensor. PC gets the spot image information through data acquisition and transmission unit, runs the beam quality testing software, obtains the average wave-front slope information by calculating the centroid of the spot. In the next step, the wave-front of laser beam is obtained by means of the model algorithm, the intensity and phase information of the laser beam is obtained. Finally, the parameters of laser beam are calculated according to the Wegener method.

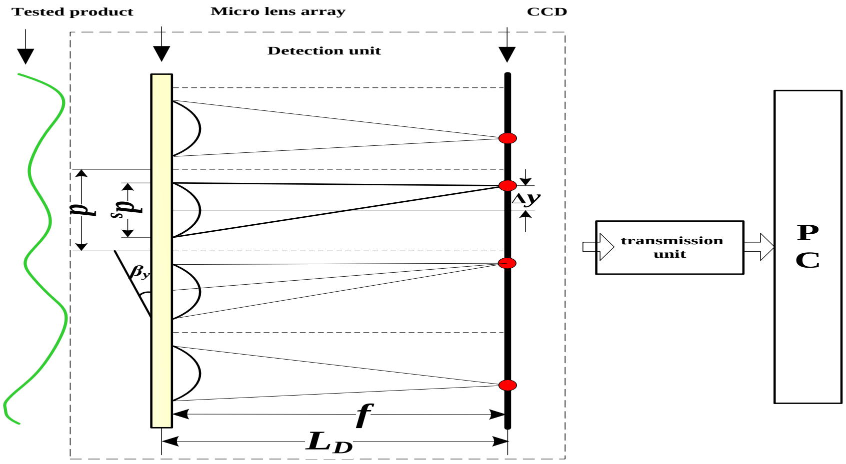

Fig.1 Principle block diagram of M2 factor by micro lens array method

3. Instrument design and Implementation

3.1 Design and implementation of laser spot detection unit

In the ISO15367-2 international standard, the main design parameters of the detection unit include center distance of adjacent aperture, sub aperture diameter, distance from micro lens array to CCD detector, focal length of micro lens, as shown in Figure 1. D is the distance between adjacent aperture centers, ds is the diameter of sub aperture, LD is the distance from micro lens array to CCD detector, F is the focal length of the micro lens. These parameters determine the angular dynamic range of the instrument, the sensitivity of the wave-front and the accuracy of the measurement [9].

Analysis of main technical parameters

（1）Angular dynamic range

Angular dynamic range is the maximum wave front tilt which can be detected by the detecting unit [10]. In Figure 1, when micro lens array integrated with CCD, $L_D \approx f$, if $\mathrm{d}_s \approx d$, under ideal conditions, the radius of focal spot is Airy disk ρ, The angular dynamic range of the instrument is expressed as

$$\beta_{y,max} = \frac{\Delta y_{max}}{L_D} = \frac{\frac{d}{2}-\rho}{L_D} = \frac{\frac{d}{2}-A\frac{\lambda f}{d}}{L_D} = \frac{d}{2f} - A\frac{\lambda}{d} \tag{2}$$

In formula (2), When the sub lens is round, the system coefficient is A=1.22, When the sub lens is a square, A=1[11]. From formula (2), Angular dynamic range depends not only on the distance between the adjacent sub apertures, but also on the size of the focal length.

（2）Wave-front sensitivity

Wave-front sensitivity is the ability of the detector to detect the smallest displacement of the focal spot. It mainly depends on the detector noise as well as the internal geometry design. It directly affects the application scope and conditions of the detection unit. If the lens array aperture index $\mathrm{F} = \frac{f}{d}$, d is the diameter of aperture, CCD pixel size is P, spot positioning accuracy is K pixels, according to the triangle theorem$\frac{\Delta \mathrm{W(x,y)}}{d} = \frac{\Delta x}{f} + \frac{\Delta y}{f}$,The wave front sensitivity is expressed as

$$\Delta \mathrm{W(x,y)}_{min} = \frac{d}{f}(\Delta x_{min} + \Delta y_{min}) = \frac{\Delta x_{min}+\Delta y_{min}}{F} = \frac{2KP}{F} \tag{3}$$

（3）Wave-front measurement accuracy

Considering the measurement accuracy of micro lens array, influencing factors mainly include two aspects. One is whether the micro lens is matched with the position of the ideal imaging position and the actual spot image on CCD, the other is the number of micro lens.

When considering the first factor, the centroid position of the laser beam and the optical axis of the micro lens need to be fully aligned, which can reduce the coma, improve the measurement accuracy. When considering second factors, only when the spot covers enough pixels, the accuracy of centroid detection can be improved, at least 4x4 pixels are required to cover the light spot. Therefore, the number of micro lens is one of the problems to be considered in improving the measurement accuracy. A micro lens is a discrete sampling of the laser wave-front. When the number of micro lenses are chosen, the more accurate the sampling of the wave-front is, the more accurate the wave-front reconstruction is. But the number of the micro lens is more, the total area is certain, the diameter of each micro lens will be reduced, and the angle of the micro lens will be smaller. So, we should compromise to choose the number of micro lenses.

In addition, the accuracy of the wave-front measurement also depends on the wave-front fitting method and the centroid detection accuracy. When the wave-front is reconstructed by using Zernike polynomials [11],[12], Zernike polynomial order and centroid detection accuracy are the main factors that affect the accuracy of wave-front measurement. For a given measurement, there is usually a minimum requirement for spatial resolution. The minimum value can be determined in several ways. If the system is used to calculate the Zernike mode and number, then, the sub aperture number needs to be larger than the mode number, or to determine the minimum spatial resolution according to the prior knowledge of the spatial resolution of the wave-front.

Determination of parameters of micro lens array

Sub spot radius regards the radius of Airy disk as a reference, The sub spot radius is larger than two pixels, which can reach the minimum requirement of the accuracy of the centroid calculation. That is,$\rho \geq 2\mathrm{P}$, the required focal length is that $f \geq 2Pd/A\lambda$, spot size will become larger in the state of aberration, so we should separate the measured wave-front. Firstly, the separation between the spot and the spot is ensured. So the spot size should be smaller than the diameter of the value of 1/q the sub lens.

According to ISO15367-2 international standard, to avoid overlapping sub spot, the required focal length is $f < d^2/2A\lambda$. To minimize the dynamic range and the crosstalk between the spot, the required focal length is

$$f < 2d^2/5\lambda \tag{4}$$

Combined (2) and (4), When the wave-front distortion is larger, the focal length of the micro lens is required. When the wave-front distortion is smaller, the focal length of the lens is longer. Small focal length can increase the dynamic range of the detector, but it will also introduce uncertainty factors.

From above analysis, When the lens is round, that is A=1.22, the pixel size is P=6.45um, CCD detection surface size is 9.0mm×6.7mm, Micro lens array size is 12mm×12mm. The limiting condition of the focal length f of the micro lens is calculated as shown in table 1.

Table 1 The limiting conditions of the micro lens focal length f (unit: mm)

Restricted expression of	the diameter of sub aperture d				
	0.11	0.13	0.15	0.25	0.3
$f < d^2/2A\lambda$	7.8	11.0	14.6	40.5	58.0
$f < 2d^2/5\lambda$	7.6	10.7	14.2	39.5	56.9
$f \geq 2Pd/A\lambda$	1.8	2.2	2.5	4.2	5.0
statistical results	1.8<*f*<7.6	2.2<*f*<10.7	2.5<*f*<14.2	4.2<*f*<39.5	5.0<*f*<56.9

By analyzing the parameters of the detecting unit, the final selection of the micro lens array model is APO-Q-P150-F3.5 (633). The basic parameter of the micro lens array is the diameter of the sub lens, that is $d = 150\mu m$, the focal length of the sub lens is $f_{E,f} = 3.5mm$, $f_{E,b} = \frac{R_C}{n-1} - \frac{T}{n} = \frac{1.6mm}{1.457-1} - \frac{1mm}{1.457} = 2.814mm$, which satisfies the constraint conditions for table 1.

3.2 Selection of CCD image sensor

When the instrument is realized, the micro lens array needs to be integrated with the CCD image sensor to form the laser signal detection unit. The array size of the micro lens array according to the above selection is $12mm \times 12mm \times 1mm$, The photosensitive surface of CCD sensor is selected to be less than $12mm \times 12mm \times 1mm$. Therefore, select LU165M as the sensor produced by the Canadian's Lumenara company. The pixels number of the sensor is 1392×1040, the pixel size is 6.45μm×6.45μm, the size of the photosensitive surface is about 9.0mm×6.7mm, which meet the integration requirements, And the spectral range of the tested product is from 400nm to 1100nm. The spectral response curve after changing the infrared filter chip window2 of LU165M to K9 glass is shown in Figure 2, which can meet the requirements of the instrument test.

3.3 Design and implementation of synchronous trigger signal generator

The design of the synchronous trigger signal mainly considers the accurate acquisition of the low frequency pulse laser and the high speed transmission of the spot information [13], Instrument uses the synchronous trigger pulse at the moment of laser emission, opening the shutter of LU165M image sensor to ensure the camera to capture the pulse laser spot information and improve the signal to noise ratio of the system. The laser spot data captured by the USB interface is transmitted to the host computer. The generation of the synchronous trigger signal is shown in Figure 3.

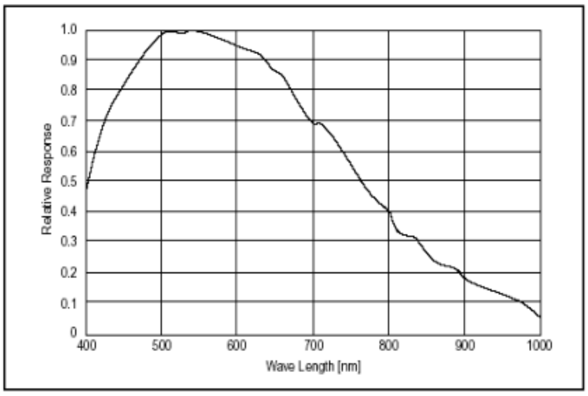

Fig.2 CCD spectral response curve

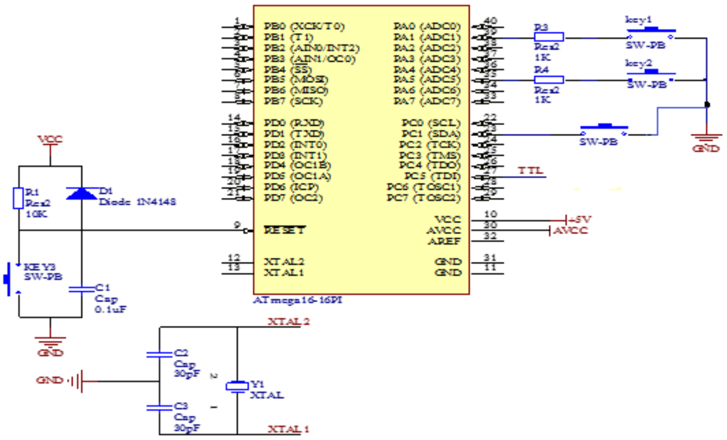

Fig.3 Principle diagram of synchronous trigger signal generation

3.4 Software algorithm design and Implementation

Software algorithm design

Based on the theory of physical optics scalar, side axis laser beam can be expressed by Wegener distribution. Wegener distribution is defined in the four dimensional quadrant, Expression is as

$$\langle x^m y^n u^p v^q \rangle = \int (x-\bar{x})^m \, (y-\bar{y})^n (u-\bar{u})^p (v-\bar{v})^q h(x,y,u,v) d_{\bar{r}} \qquad (5)$$

In formula (5), indexes m, n, p and q are integers. $h(x,y,u,v)$ is the Wegener distribution function for the light beam. P is for beam power, x and y are the coordinates of the cross section in the direction perpendicular to the propagation, v and u respectively represents the direction of propagation, among which $d_r = d_x d_y d_u d_v$.

Three dimensional beams are usually shown in the following, which has ten two-order moments.

$$\langle x^2 \rangle, \langle xu \rangle, \langle u^2 \rangle, \langle y^2 \rangle, \langle yu \rangle, \langle v^2 \rangle, \langle xy \rangle, \langle uv \rangle, \langle xv \rangle, \langle yv \rangle$$

Also can be expressed as matrix

$$\mathrm{V} = \begin{vmatrix} \langle x^2 \rangle & \langle xy \rangle & \langle xu \rangle & \langle xv \rangle \\ \langle xy \rangle & \langle y^2 \rangle & \langle yu \rangle & \langle yv \rangle \\ \langle xu \rangle & \langle yu \rangle & \langle u^2 \rangle & \langle uv \rangle \\ \langle xv \rangle & \langle yv \rangle & \langle uv \rangle & \langle v^2 \rangle \end{vmatrix} \qquad (6)$$

In formula (6), V is the beam parameter matrix at any position in the beam propagation path. All the important elements in V have clear physical meaning and are closely related to the important parameters of the beam.

Spatial two order moments $\langle x^2\rangle$, $\langle y^2\rangle$ and $\langle xy\rangle$ can be used to determine the beam width at the position of z $= z_0$ in the direction of propagation, and can be expressed as

$$d_x = 4\sqrt{\langle x^2\rangle}$$

$$d_y = 4\sqrt{\langle y^2\rangle} \tag{7}$$

Similarly, angle two-order moments $\langle u^2\rangle$, $\langle v^2\rangle$ and $\langle uv\rangle$ are the products of two order moments $\langle x^2\rangle$, $\langle y^2\rangle$ and $\langle xy\rangle$ in the far field, the beam divergence angle θ is

$$\theta_x = 4\sqrt{\langle u^2\rangle}$$

$$\theta_y = 4\sqrt{\langle v^2\rangle} \tag{8}$$

The hybrid moment represents R the radius of curvature in the direction of parabola of the wave-front

$$R_x = \frac{\langle x^2\rangle}{\langle xu\rangle}$$

$$R_y = \frac{\langle y^2\rangle}{\langle yv\rangle} \tag{9}$$

Import S Gauss matrix of optical system, beam matrix P via a linear and non-distorted optical system can be expressed as

$$P_Z = S(z, z_0)\cdot P_{z_0}\cdot S^T(z, z_0) \tag{10}$$

The invariants in the propagation process are $M^4 = 4K^2\sqrt{detP}$, among which k is wave number andk $= \frac{2\pi}{\lambda}$. For simple scattered beam M^4 can be divided into the product of the beam propagation factor.

$$M_x{}^2 = \frac{4\pi}{\lambda}\sqrt{\langle x^2\rangle\langle u^2\rangle - \langle xu\rangle^2}$$

$$M_y{}^2 = \frac{4\pi}{\lambda}\sqrt{\langle y^2\rangle\langle v^2\rangle - \langle yv\rangle^2} \tag{11}$$

For the Gauss laser beam with spatial coherence, the First - and two - order moments of variables x, y, u and v in the spatial and angular domain can be calculated by using the data obtained from the micro lens array.

$$\langle x^2\rangle = \frac{\sum_{ij}(x_{ij} - \langle x\rangle)^2 I_{ij}}{\sum_{ij} I_{ij}}$$

$$\langle u^2\rangle = \frac{\sum_{ij}(\beta_{ij} - \langle\beta_x\rangle)^2}{\sum_{ij} I_{ij}} + \frac{1}{k^2}\cdot\frac{\sum_{ij}\left(\frac{1}{I_{ij}}\right)(\partial I/\partial x)_{ij}{}^2}{4\sum_{ij} I_{ij}}$$

$$\langle xu\rangle = \frac{\sum_{ij}(\beta_{x,ij} - \langle\beta_x\rangle)\cdot(x_{ij} - \langle x\rangle)\cdot I_{ij}}{\sum_{ij} I_{ij}} \tag{12}$$

Among which, I_{ij} indicates the strength of micro lens array sub beam whose Indexes is (i, j).

$$\langle x\rangle = \frac{\sum_{ij} x_{ij} I_{ij}}{\sum_{ij} I_{ij}}$$

$$\langle\beta\rangle = \frac{\sum_{ij}\beta_{ij} I_{ij}}{\sum_{ij} I_{ij}} \tag{13}$$

Beam divergence angle, beam propagation factor, beam waist position and size related parameters can be calculated by the above formula.

Implementation flow of Software algorithm

The design of software algorithm is based on 3.4.1, using the micro lens array method, we captured the laser spot image, the digital quantity of the light spot intensity and the phase information is transmitted to the upper computer through the USB port. The upper computer runs the software flow shown in Figure 4, the beam quality of the tested laser can be implemented.

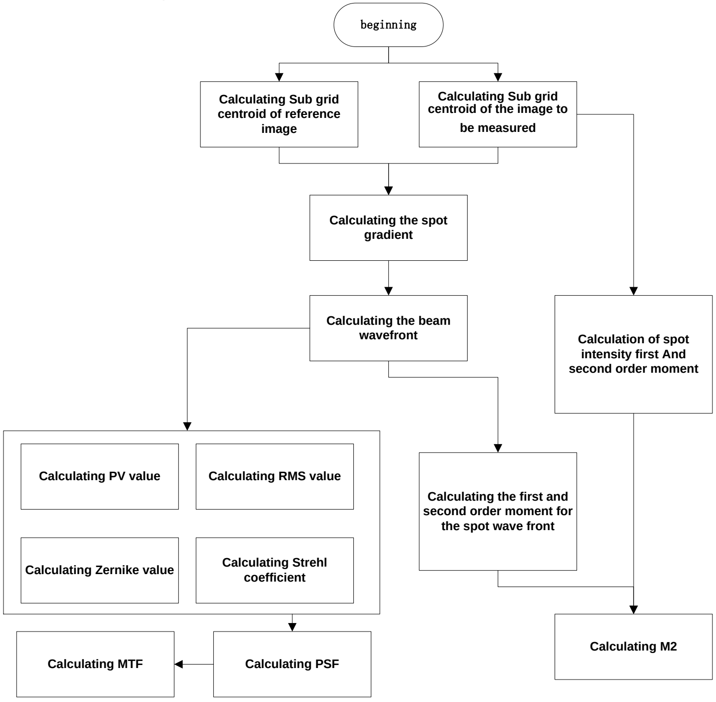

Fig.4 Test software flowchart

M2: x 1.34208885

M2: y 1.47484320

Beamwidth: x 1.280952 [mm]

Beamwidth: y 1.313251 [mm]

Divergence: x 0.978808 [mrad]

Divergence: y 0.944505 [mrad]

Waistdiameter: x 1.104741 [mm]

Waistdiameter: y 1.258109 [mm]

Ralylenggth: x 1128.660132 [mm]

Ralylength: y 1332.030303 [mm]

Waistpos: x -1308.686609 [mm]

Waistpos: y -1390.4126.7 [mm]

Fig.5 Instrument test results

Fig.6 Appearance of instrument

4. Instrument test and result analysis

In actual test, the user sets the appropriate mode number of Zernike polynomials [12], reference spot, the size of the spot capture window, the focal length of the lens according to the measurement requirements. Then, the spot area of the array is identified by the region labeling and the judging algorithm, the centroid and intensity of each sub spot area are calculated. The intensity distribution of light spot smoothing can be obtained by interpolating the array spot by image interpolation algorithm, and the relative strength spatial characteristic parameters can be calculated. The focal point of the actual array spot will deviate from the optical axis of each micro lens namely the centroid of the reference spot. The center point offset of each sub spot was obtained, which is proportional to the inclination of the wave front [13]. We calculate the local tilt of each sub spot, use model method and interpolation algorithm to reconstruct the wave-front, obtain the phase distribution of the laser beam and calculates the relevant wave front characteristic parameters. At last, we used the Wegener method to calculate the transmission parameters of the current beam associating with the spot intensity data and wave front phase data. The test results of the instrument are shown in Figure 5 and the appearance of the instrument is shown in Figure 6.

5. Conclusions

In this paper, the intensity and phase distribution of laser spot are obtained by using the micro lens array method with single sampling. The method has advantages such as no moving parts, overcoming the measurement error introduced by moving parts, reducing the complexity of the system, short measurement time and good real-time performance. The instrument used the moment theory to calculate beam width, beam divergence angle and beam quality factor of the laser beam based on the Wegener distribution. The spectrum range of the tested product is from 400nm to 1100nm. The measurement precision of the instrument beam quality factor is 5%. A number of performance parameters of the laser are given. The comprehensive evaluation of the laser beam quality is realized, which lays the foundation for the realization of the miniaturization of the beam parameter measurement instrument.

Reference

[1] JING Maohua. Beam quality evaluation of coherently combined laser beams [J]. Vol. 25, No.2, 2013, 367-370.

[2] CAO Changqing, ZENG Xiaodong. Evaluatiing the beam quality of semiconductor lasers [J]. J. Infrared Millim.Waves, Vol. 30, No.3, 2011,276-278.

[3] LI Lei, ZANG Jingfeng. Measurement of laser beam quality of double slits scanning method[J]. Laser technology, Vol. 39, No.6, 2015, 845-849.

[4] WANG Caixia. Design of the Measurement System for Laser Beam Quality M2 Factor[J].Process Automation Instrument, Vol. 31, No.11, 2010, 51-54.

[5] JIN Aijun, Hou Jing, Jiang Zongfu. Evaluation of the beam quality of supercontinuum soure using supercontinuum M2 factor[J].Chinese J Lasers, Vol. 40, No.5, 2013,0502006-1-0502006-5.

[6] MA Haotong, Xi Fengjie, Zhou Pu, et al. Measurement of M2 factor of 1064 nm pulsed laser based on crossed defocus gratings[J]. Acta Optica Sinica, Vol. 30, No.3, 2010, 821-826.

[7] ZHOU Xiaobin, LUAN Yadong, SHI Leilei, et al.Structural parameters calibration of Hartmann-Shack sensor based on known spherical wavefront [J].Journal of Applied Optics, Vol. 36, No.6, 2015, 909-912.

[8] WU Zhuo-liang, ZHAO Shang-hong, CHU Xing-chun, et al. Analysis of Beam Quality for Spectral Beam Combining System with Microlens Array [J]. Opto-Electronic Engineering, Vol. 38, No.11, 2011, 29-34.

[9] LIU Minshi, WANG Xiaoman, JING Wenbo, et al. Design of Parameters of Shack-Hartmann Wave-front Sensor for Laser-Beam Quality Measurement[J], ACTA OPTICA SINICA, Vol.33, No.3,2013,0328002-1-0328002-5.

[10] ZHANG Jinzhou, ZHANG Zhongyu, ZHANG Xuejun, et al. Algorithm for Extending Dynamic Range of Shack-Hartmann Wavefront Sensor[J], ACTA OPTICA SINICA, Vol.31, No.8,2011, 0812006-1-0812006-5.

[11] WANG Yan, FU Ruimin, LIAO Zhibo. Wavefront Reconstruction Algorithm Based on Sparse Aperture [J]. SPACECRAFT RECOVERY & REMOTE SENSING, Vol. 36, No.5, 2015, 51-57.

[12] XIE Wenke, GAO Qiong, MA Haotong, et al. Zernike modal wavefront reconstruction algorithm based on model selection [J].Acta Phys. Sin. Vol. 64, No.14, 2015, 144201-1-144201-6.

[13] ZHAO Tianzhuo, FAN Zhongwei, YU Jin, et al. Multi-Parameters Real-Time Monitoring System for Low-Frequency Laser Beam[J], CHINESE JOURNAL OF LASERS, Vol.37, No.12, 2010,:3086-3090.