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Effects of laser facula detector array parameters on measurement accuracy of far-field beam quality

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ABSTRACT

The detector array parameters will greatly affect the measurement accuracy of beam quality at target. In this study, the relations of the parameters with encircled power ratio and the beam radius at target were further analyzed. Since the beam at target is a Gauss-like beam, the effects of detector array's spatial resolution, effective testing area, systematic dynamic range, and surface response homogeneity on measurement accuracy of beam quality were analyzed quantitatively with numerical simulation. The results show that among all influence factors, the measurement accuracy of beam radius was greatly affected by the detector's normalized size and dynamic range, but slightly by normalized resolution and surface response homogeneity. These results were successfully applied in design of detector array and achieved good effect. The experimental data and theory are well consistent.

1. Introduction

Under the effects of turbulence and thermal blooming, the high-power laser during atmospheric transmission will change largely in terms of far-field power density distribution and beam quality [1–3]. In order to obtain the beam quality at target, usually the time-space distribution of power density at target is directly measured using facula detection array, and then the centroid and beam quality at target are calculated on basis of facula distribution and encircled energy distribution. These detectors are rich in types and structures. Usually, tens or hundreds of discrete samplers are arranged on the target surface. After passing the samplers, the laser beam is received by a photoelectric detector and finally the light intensity of each sampler is computed by the processing circuit and software; the time-space distribution of facular power density is obtained [4–11]. Despite the appearance of various detector arrays, because of differences in parameter designing, the parameters will differently affect the measurement accuracy of beam quality at target. However, there are few reports in this aspect. The objectives of this study are to investigate the effects of detector array parameters (e.g. resolution, detector size, dynamic range, and detector homogeneity) on measurement accuracy of beam quality at target. Based on the influence degrees on measurement accuracy, the parameters were optimized and matched, so that the accuracy was controlled to be less than 10%. This study provides guidance for designing of detector array parameters.

2. Test model

2.1. Beam quality test model

Many methods can be used to measure and evaluate beam quality, including beam quality β factor, M^2 factor, encircled power ratio BQ, and Strehl ratio SR; these methods possess respective pros and cons and apply to different fields [12–17]. In this paper, the detector array is used to measure the beam quality at target of high-power laser after atmospheric transmission, and thus we care about the laser system's focusing ability. Therefore, β factor was selected to evaluate beam quality. β factor is defined as (1):

$$\beta = \frac{\theta_a}{\theta_i} = \frac{r_a}{r_i} = \frac{r_a D}{\varepsilon \lambda L} \quad (1)$$

where θ_a and θ_i are the measured and ideal divergent angles of the beam at target respectively; r_a and r_i are the measured and ideal beam radius at target respectively; D is the diameter of the divergent beam; λ is laser wavelength; L is transmitting distance; ε is a constant related to the emitting system's obscuration ratio.

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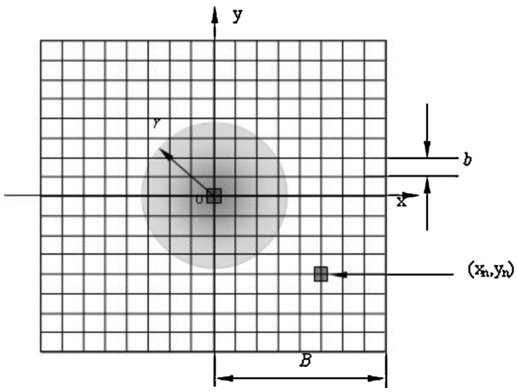

Fig. 1. Sketch map of the detector array.

Therefore, the only factor affecting beam quality β is the real beam radius at target.

2.2. Detector array measuring model and algorithm

The sketch map of the detector array is showed in Fig. 1. The detector array is composed of several discrete detection units in regular and uniform arrangement. Each grid intersection is installed with a detecting unit. There are $M \times M = \mathrm{N}$ units, with an area δ, spacing b, size $2B$, and total area S.

When a laser beam is received by the detector array, each unit detects the laser power P_n at the corresponding site. The average power density $I(x_n, y_n)$ at this site can be obtained by weighted effective areas of the detecting unit, and the average power densities of all detecting units can be added to obtain the spatial intensity distribution $I(x, y)$.

The 1-order discrete expressions at x-axis and y-axis are:

$$\bar{x} \approx \frac{1}{P} \iint\limits_{S} xI(x,y)dxdy = \frac{\sum_{n=1}^{N} x_n (b \times b)\frac{P_n}{\delta_n}}{\sum_{n=1}^{N} (b \times b)\frac{P_n}{\delta_n}} = \frac{\sum_{n=1}^{N} x_n \frac{P_n}{\delta_n}}{\sum_{n=1}^{N} \frac{P_n}{\delta_n}} \tag{2}$$

$$\bar{y} \approx \frac{\sum_{n=1}^{N} y_n \frac{P_n}{\delta_n}}{\sum_{n=1}^{N} \frac{P_n}{\delta_n}} \tag{3}$$

where $(\bar{x}, \bar{y})$ is the position of the beam centroid at time t_i corresponding to a single frame, and its time series is the centroid's changing curve with time $\bar{x}(t_i), \bar{y}(t_i)$. After the beam centroid is located, an encircled energy method can be used to compute beam radius: namely with the centroid $(\bar{x}, \bar{y})$ as the center of a circle, draw circles with varying encircled radius r, and plot the changing curve $K(r)$ of power percentage K with r in the circles:

$$K(r) = \frac{P_r}{p} = \frac{\iint_{S_r} I(x,y)dxdy}{\iint_{S} I(x,y)dxdy} \approx \frac{\sum_{\sqrt{(x_n-\bar{x})^2+(y_n-\bar{y})^2} \le r} \frac{P_n}{\delta_n}}{\sum_{n=1}^{N} \frac{P_n}{\delta_n}} \tag{4}$$

With $K(r)$, the r corresponding to an encircled percentage can be obtained.

Encircled power percentage K changes among faculae with different intensities; $K = 47.9\%$ for a homogeneous annular beam with obscuration ratio of 0.5, but $K = 86.5\%$ for Gauss beams [18].

The type, shape and obscuration ratio of the emitted beam are closely related to the encircled power rate of the beam at target, and thus before analysis of beam quality at target, the encircled power rate should be determined on basis of the emitted beam's characteristics. Fig. 2 shows after emission of an annular beam (obscuration ratio 0.5), the real beam distribution after atmospheric transmission measured by detector array, as well as the sectional intensity distribution at target and the encircled power curves of the ideal Gauss beam and under the ideal condition.

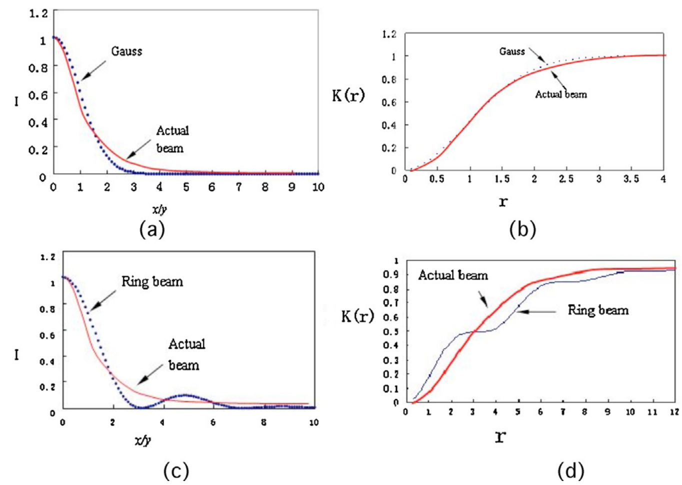

Fig. 2. Comparison of distribution and encircled power ratio between different types of emitted beams and the beams at target. (a) and (b) show the comparison between Gauss beams and real beams at target; (c) and (d) show the comparison between angular beams and the real beams.

Fig. 2 shows that under the effects of atmospheric factors such as turbulence, the real beams at target are largely different from the ideal beams in terms of shape and encircled power ratio, but are close to Gauss beams. Therefore, Gauss beams can be used in real engineering application: encircled power ratio $K = 86.5\%$, which is used throughout the following analyses.

3. Mechanisms about the effects of major parameters on measurement accuracy of beam quality

The above analyses indicate that among the detector array parameters, the measurement accuracy of beam quality is mainly affected by the real beam radius at target, whose measurement accuracy is decided by the measurement accuracy of encircled power percentage. For a random encircled power percentage curve, if there is error ΔK in measurement and computation of encircled power ratio, then ΔK will lead to beam radius error Δr. A large K will lead to small r, and vice versa. When K is changing, the same ΔK will lead to varying Δr. When $K \sim r$ curve slope is small, the same $\Delta \mathrm{K}$ will lead to large Δr. Noticeably, the generation of ΔK is mainly originating from the measurement error of P in computation of K. Clearly, because of limitation in detector performance, the incomplete measurement of total intensity P will cause positive error in ΔK, thus making r smaller. The relation between ΔK and Δr is showed in Fig. 3.

The effects of array detection system parameters on beam quality are mainly reflected in their effects on encircled energy ratio, specifically:

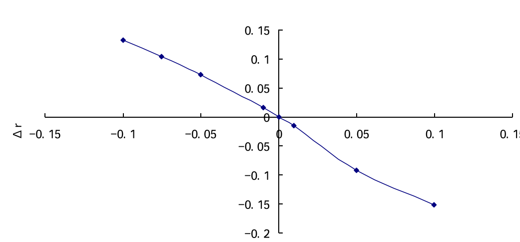

Fig. 3. Relation between encircled power ratio error ΔK and beam radius error Δr.