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Automated alignment research on off-axis eight-pass laser amplifier

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Abstract: We present a technical research experimentally demonstrating automated alignment on off-axis eight-pass laser amplifier. The mentioned technique aims to replace manual alignment method with automatic alignment system on the multipass complex laser amplifier, of which the efficiency, accuracy, and output beam quality would improve spectacularly. This technique realizes precise reference mark of pinhole spatial centre position in the spatial filter of the off-axis eight-pass laser amplifier via main laser lighting and image relaying system. The far-field facula is processed by edge detection so that the beam pointing centre is obtained. Based on the difference between the beam centre position and reference, we realizes closed loop automated alignment on the amplifier system via two-dimensionally controlling specific reflector frames. Additionally we indicate that the experimental results of the research fairly satisfied requirements for efficiency and accuracy of the off-axis eight-pass laser amplifier, and verified feasibility of the alignment technique applied in the amplifier as well.

Key words: laser amplifier； off-axis eight-pass amplifying； automated alignment； edge detection

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Off-axis multipass laser amplifiers are widely used in high power solid-state lasers for high extraction efficiency, ultrahigh gain and strong capability of suppressing self-oscillation or parasitic oscillation[1-4]. Especially for high-power Nd:glass or Yb:YAG laser systems, as the stimulated emission cross (σ) is relatively small, the extraction efficiency of single-pass amplification is very low and multipass laser amplifiers were strongly desired[5]. Until now, off-axis two-pass or four-pass amplifiers have been proposed extensively[6-8]. Recently, a novel off-axis eight-pass amplifier was proposed by our team, and the extraction efficiency was significantly improved[9-10]. However, since the laser goes through the gain medium for eight times, the beam alignment with high precision is required to guarantee the good beam quality. Besides, it is conventionally known that reference is commonly used in alignment approaches. Generally these approaches compare the position of near-field and far-field reference with the actual position first then calculate the position error so as to align laser beam. Typically, the National Ignition Facility (NIF) four-pass architecture utilized stable pinholes coordinated with light source as reference for both near-field and far-field alignment and charged-coupled device (CCD) cameras to gain reference. In NIF, alignment system performance mainly depends on the accurate position of the reference, and the facility is expected to reach an accuracy of 50 μm RMS over the 192 beams with its alignment system[11]. Additionally, one significant approach from Shanghai Institute of Optics and Fine Mechanics adopts image acquisition card with VC++ programming to process image collected from CCD in actual time, it could successfully reach a quick alignment on liber coupling laser beam in laboratory, and the accuracy is around 4 μrad[12]. Moreover, there is an impressive approach from the Laser Fusion Research Center shows that beam alignment can be adjusted with only one near-field camera based on beam frequency characteristics instead of reference. It analyzes two-dimensional power spectral density of the near-field image in order to acquire beam pointing errors directly, leading to a good improvement on efficiency and low cost[13]. Several approaches mentioned above illustrate that a variety of adjustment could be applied in different alignment systems in order to improve laser system.

In this essay, we develop a comprehensive technique to build an automated alignment system, which leads a spectacular

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incremental efficiency and accuracy for off-axis eight-pass laser amplifier. First, we create pinhole image as reference via combination of illumination alignment beam and image relaying linear optical information processing system, as well as pinhole plate in the spatial filter. By employing edge detection, we could confirm actual beam spot centre position, and the position error could also be calculated since the actual beam position and reference have been known. Then we regard error as feedback signal, afterwards drive step motors so as to control reflector frames two-dimensionally to meet error correction, the automated alignment is achieved at last. The alignment system would operate a closed loop supervisory alignment control since it monitors the beam position in actual time.

1　Experimental context

Literally, the off-axial eight-pass laser amplifiers developed from traditional off-axial four-pass amplifier via polarization control[14]. In the amplifier, as input laser beam pass polarizer P1 (P polarization), the beam would keep its polarization via birefringence crystal, then enter the traditional off-axial four-pass amplifier through polarizer P2 (S polarization). Been amplified by four-pass amplifier, laser beam pass birefringence crystal second time with 90° rotated polarization, next reflect on P1 to reflector M, the laser beam would transmit along the original path reversibly, it can be deduced that the polarization of the beam would rotate 90° third time the beam go through birefringence crystal. Afterwards been amplified by four-pass amplifier another four times, laser beam output from the off-axis eight-pass amplifier since its polarization remained forth time pass through birefringence crystal[10]. The mechanism is shown as Fig. 1.

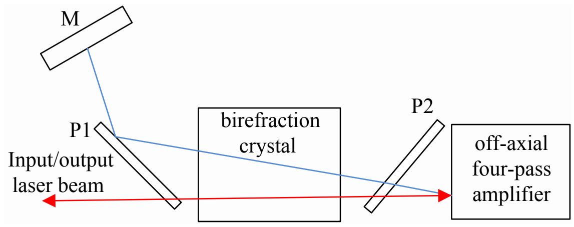


Fig. 1　Basic mechanism of off-axis eight-pass laser amplifier

Consider the demand for alignment on the complex multi-pass optical system and the optical formation on the premise, we design an appropriate alignment configuration in the specific light path. In this alignment system, we adopt a couple of translatable concave lens installed with translation platform as the alignment lens (AL) for expanding alignment beam so as to illuminate full 4 pinholes in spatial filter 1, then Charged Coupled Device (CCD) cameras (resolution 1280×1024, pixel size 4.8 μm×4.8 μm, operation wavelength 1053 nm) can obtain pinhole imaging pictures of both sides via image lens (IL), at this point, target surface of the CCD gain leak light of the beam with a very low energy of 300−400 nJ. On the one hand from CCD1 we can get 1st, 3rd, 5th, 7th pass pinhole image with AL1 (f=−350 mm) and IL1 (f=160 mm) in the path, on the other hand from CCD2 we can get 2nd, 4th, 6th, 8th pass pinhole image with AL2 (f=−200 mm) and IL2 (f=160 mm) in the path, Fig. 2 shows the laser path.

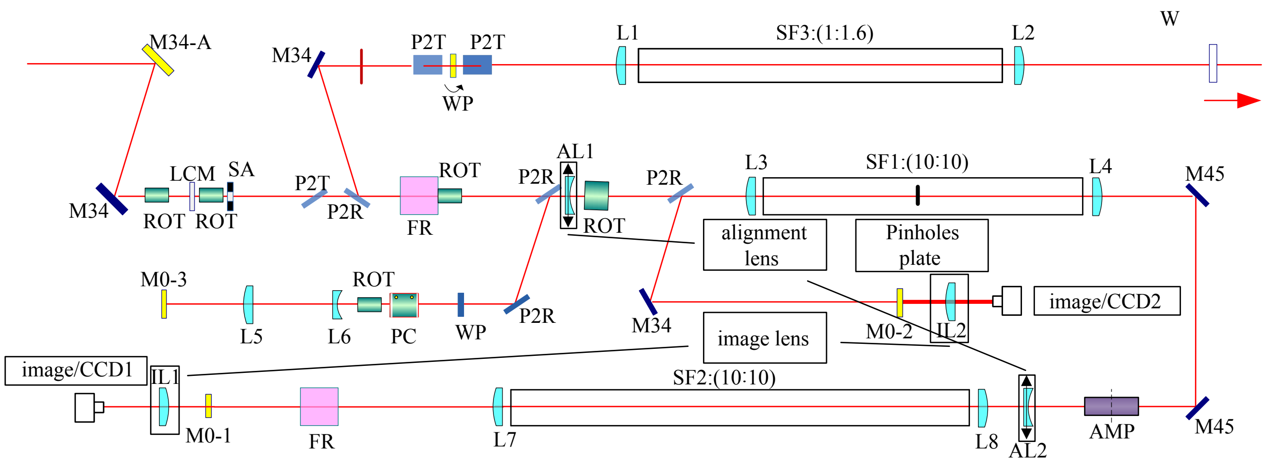


Fig. 2　Off-axis eight-pass laser path

Initially, CCDs obtain pinhole image, then the upper computer acquires and analyzes marginal pixel data to confirm centre point of pinhole as reference. It is worth mentioning that our alignment progress should be implemented pass-by-pass. There is no longer need for the alignment lens so we move them out of the path in advance. 1st pass corresponds to M34-A reflector frame, 2nd pass corresponds to M0-1 reflector frame, 3rd pass corresponds to M0-2 frame, 4th pass will get alignment once 3rd pass gets alignment since it is conjugate, 5th pass corresponds to M0-3, all of 6th, 7th, 8th pass are conjugate therefore once 5th pass gets alignment successfully, so do they. In case laser beam alignment should be implemented pass-by-pass, we equally divide the reference into four squared parts, which means 8 parts in sum. Fig.3 illustrates the reference design.

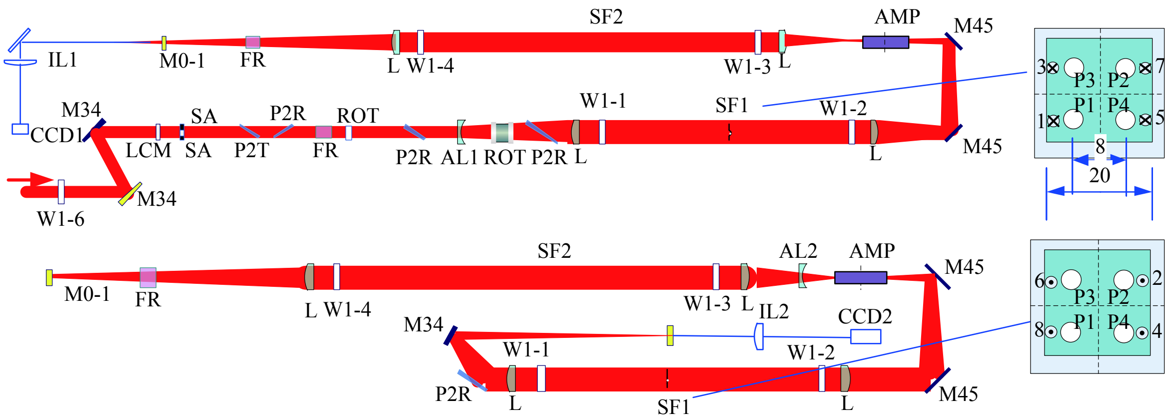


Fig. 3 Alignment reference design

Have reference prepared in specific software, we utilize CCDs to collect beam spot information of the laser beam via lens for expanding. At this point, we prefer using ant colony algorithm[15] to process image of the beam spot so as to realize edge detection. In each part, the bionic algorithm regards pixel gray scale as biotin density in this situation. It could be appreciated that putting ants (working unit) on random pixel, allowing them follow the trail of biotin to form path information (partial image information). Therefore, after the algorithm performed for proper times, we can define the image edge to calculate actual beam centre point, and obtain error after compare position of the beam centre point with that of the reference [16]. The progress can be comprehended as Fig.4.

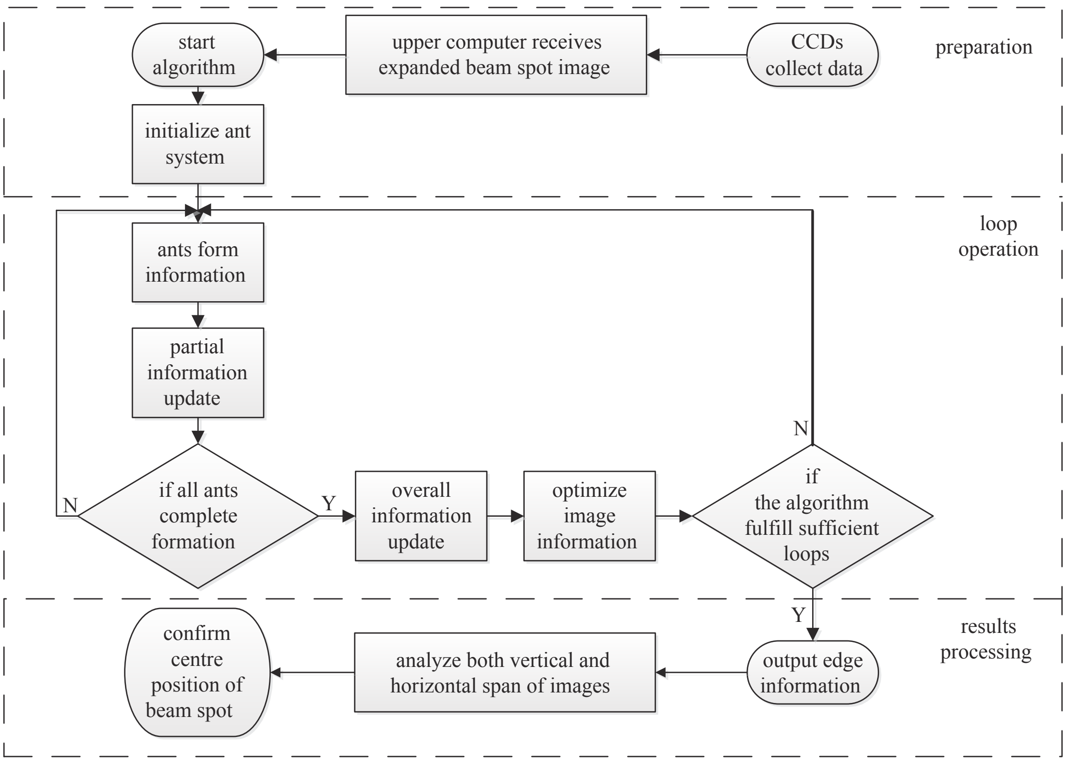


Fig. 4 Progress of edge detection

In order to correct beam pointing error, it is essential to adjust reflector frames refer to error data. For the sake of controlling reflector frames, we configure 64-subdivision step motor on each frame we need to adjust, as well as Beckhoff programmable logic controller (PLC) CX2030 to control motor drive EL7041-0052 via EtherCAT network EK1100. In this part the correspondence between pixel and motor step must be precisely clear to achieve accuracy of the alignment, due to our previous work, the one step resolution of motors is 3.6″(18 μrad). According to pixel size of CCDs and image focal distance, we could figure out the correspondence between motor movement of one step and image movement of pixel size via Eq(1). Therefore we could realize a fairly accurate motor control in terms of position error.

$$M = \frac{F \times \tan 3.6''}{A} \tag{1}$$

M is the amount movement of pixel size when the motor moves one step, F is the image focal distance and A is one square pixel length. Approximately we define the correspondence between motor step and pixel movement is 6:1, which means 6 absolutely vertical nor horizontal steps movement of the motor represents one pixel movement of the image.

We integrally develop procedures by QT development tool via C++ shown as Fig.5. Hence a closed loop automated alignment system is effectively achieved.

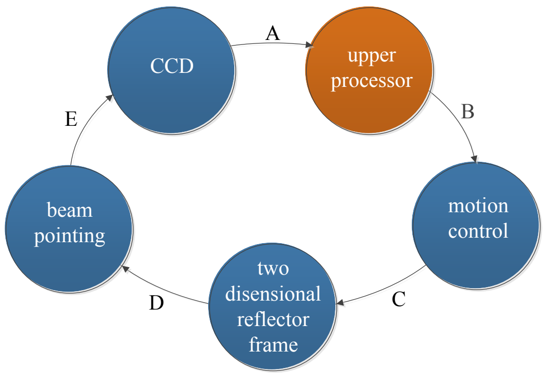


Fig. 5　Closed loop automated alignment system

The software user interface provides function buttons consists of launcher, mode configuration, progress check, and operation daily record, etc. Additionally, it demonstrates real time beam pointing by CCD, monitors the whole progress of alignment demonstrated as Fig.6.

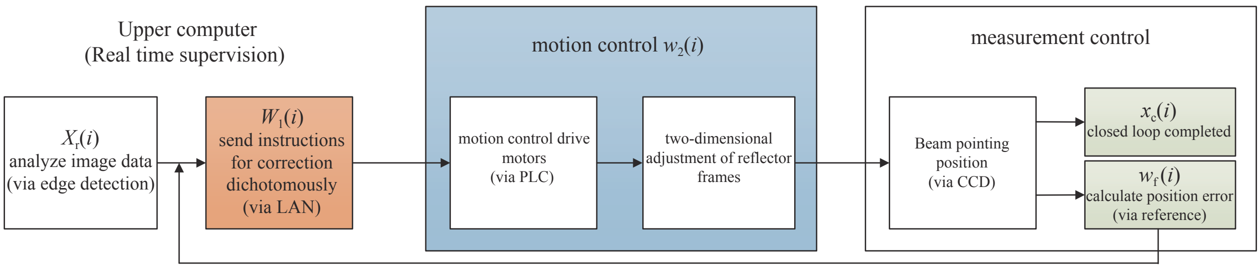
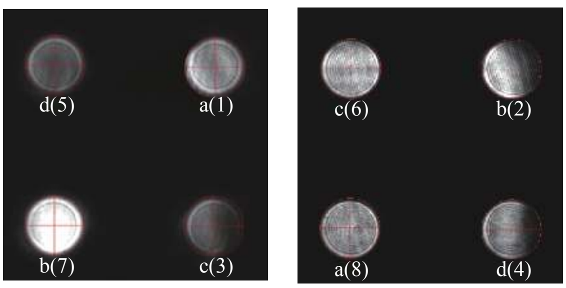


Fig. 6　Alignment progress

2　Experimental results & evaluations

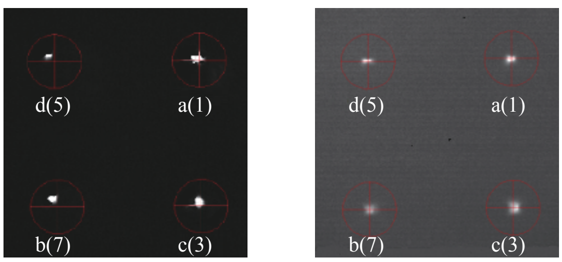
In the initial experimental section, we acquire pinhole image, then we are able to establish spot reference by figuring out the centre of circular area with high gray scale pixels, shown as Fig.7.

With the usage of interdisciplinary knowledge which can be appreciated as a union of mechanics, optics, electronics and programming, we appropriately give a brand new alignment method for off-axis eight-pass laser amplifier. Through this method, we acquire the far-field laser spot of eight passes under automated alignment, shown as Fig.8.



(a) front-oriented reference　(b) back-oriented reference

Fig. 7　Alignment reference installation



(a) far-field beam pointing before alignment　(b) far-field beam pointing after alignment with compensation

Fig. 8　Far-field beam pointing progress

In addition, with the usage of CCD we can monitor the state of beam alignment in real time. The beam alignment would be kept or adjusted if error occurred at all time by the adoption of the automated alignment system. Furthermore, this software could also be integrated into upper control software for the whole amplifier system. Since this control system has started operating in off-axis eight-pass laser amplifier, its efficiency, accuracy as well as reliability are going to be examined.

During period of amplifier manufacture, the primal adjustment method of beam alignment on the amplifier used to be manipulating rotating shaft of the reflector frame manually, and at the very beginning it approximately takes half an hour to collimate all eight passes in the amplifier, then as we become proficient, this method still takes about twenty minutes. At present, we adopt automatic control and it takes approximately 5 min to reach beam alignment. The time cost on alignment is acquired by procedure management function we programmed in the software, which illustrates automated alignment system is more efficient than manual alignment, hence contributes to satisfy the massive demand for production capacity in large laser facility.

Besides, we prefer referring to the output laser beam quality in order to evaluate the achievement of the alignment. Considered that the fault tolerance on adjustment is inevitable in the experiment, the alignment system is expected to reach an accuracy of 30 μrad with the considerate limitation on pixel size and one step resolution of the step motor. Furthermore, the experimental near-field beam quality shown as below. It can be evaluated that the amplifier could output excellent laser beam quality via the automated alignment technique, demonstrated as Fig.9.

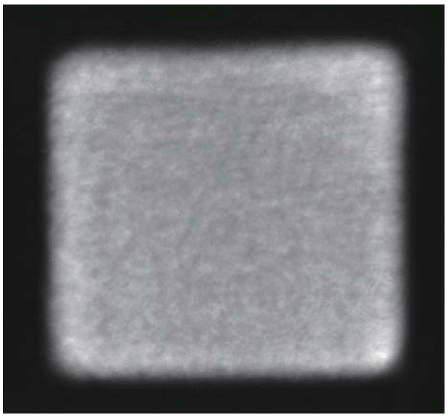


Fig. 9 Near-field laser beam quality

As to assess the reliability of the automated alignment on the amplifier, we are going to leave a proper time for system operation so as to make a valid assessment on reliability.

3 Conclusion

The automated alignment technique including optics, mechanics, electronics and communication perfectly corresponds to off-axis eight-pass amplifier which contains a wide range of factors and achieves a fairly efficient and accurate performance. Additionally, it configures actual time overall progress monitor resulting in good reliability.

Interdisciplinary application seems to be a significant way to improve the performance of the amplifier. The alignment system design is only a section for optimizing the performance of off-axis eight-pass laser amplifier. In fact, there are massive prospective jobs to accomplish. We plan to apply artificial intelligence technique in laser amplifier system. For instance, it is fairly considered useful to adopt near-field image recognition and deep learning used in spectral compensation, which might lead to a great improvement on efficiency of the alignment system.

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离轴八程放大器自动准直技术研究

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摘 要：展示了基于离轴八程激光放大器的闭环自动准直技术研究，该项技术旨在用自动准直系统取代手动光路准直的方式，明显提高了该构型复杂的多程激光放大器的运行效率、准直精度与其输出光束质量。该技术利用主激光照明和像传递系统实现离轴八程激光放大器中滤波器小孔空间位置的精确标定，通过边缘检测处理远场光斑得到其指向中心。基于光斑中心与基准间的差值，对特定反射镜架进行二维控制进行光束指向补正，从而实现离轴八程放大器系统的闭环自动准直。研究结果表明，实验结果契合离轴八程放大器系统对光束准直准确率与效率的要求，验证了该准直技术在离轴八程激光放大光路中应用的可行性。

关键词：激光放大器；离轴八程放大；自动准直；边缘检测