Coaxial combination of coherent laser beams

Hongcheng Dong (董洪成)[1,2*], Xiao Li (李 笑)[1,2], Chaoyang Wei (魏朝阳)[1], Hongbo He (贺洪波)[1], Yuanan Zhao (赵元安)[1], Jianda Shao (邵建达)[1], and Zhengxiu Fan (范正修)[1]

[1]*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*

[2]*Graduate University of Chinese Academy of Sciences, Beijing 100049, China*

[*]*E-mail: hchdong1980@126.com*

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Based on polarization state conversion, a technique for coaxially coherent combination of laser beams is introduced. Laser beams can be coaxially coupled into one beam with high combination efficiency and perfect beam quality. A polarized laser beam combination system based on master oscillator power amplifier (MOPA) configuration is developed and the efficiencies of both unit combination and the whole system are investigated. In the experiment of combining four beams with single longitudinal mode, a combination efficiency of 85.3% is achieved. It can be further enhanced by improving the stability of experimental environment and the quality of optical and mechanical components.

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For high power solid-state lasers, the output power is limited by thermal effect, nonlinear effect, and damage of gain medium. Therefore, it is hard to obtain high output intensity and good beam quality simultaneously. Combining multiple low-power coherent beams to a single one is considered to be a promising technique for the problem described above. According to this beam combination technique, a beam with both high power and good beam quality can be obtained. Generally, beam combination is divided into incoherent[1−3] and coherent combination[4−13]. It also can be classified into intra-cavity combination[4−6], extra-cavity combination[3,8−13], and coupled cavity[14]. With the advantage of reducing laser performance and improving consistency of beams, extra-cavity coherent combination based on master oscillator power amplifier (MOPA) configuration is widely studied. A recent result of 19 kW is obtained by injecting a master oscillator into a sequence of multi-kilowatt Nd:YAG zigzag slab amplifiers[10]. In this way, the system complexity is reduced because all beams are combined by only one element, which could withstand all the laser output power without damage at the far end of the system. However, the output beam through most MOPA combination is in the form of array[9−11]. The combined beam is separated in the near field but superposed through interference in the far field. Therefore, partial power of the combined beam is distributed into side lobes in the far field, which results in the central peak with only a fraction of the total power and bad beam quality. In addition, the realization of in-phase control for constructive interference is a main problem.

In this letter, we present a coaxial coherent beam combination method based on polarization conversion. In this way, higher combination efficiency and better beam quality can be obtained. Moreover, all the beamlets are not required to be the same phase, so complicated phase detection is not necessary.

When two orthogonally linear polarized beams (LPBs) with identical frequency and fixed phase difference δ_0 superpose in space, an elliptical polarized beam (EPB) is generated. The phase difference of electric fields between the main axes (long axis and short axis) of the EPB is $\pm\frac{\pi}{2}$, where the positive or negative sign depends on the rotation direction of the EPB. If a quarter wave plate (QWP) is inserted into the EPB and its optical axes (fast and slow axes) are parallel to the main axes, a new LPB can be generated. The electric vector of the LPB can be rotated any angle by a half wave plate (HWP). Therefore, the two LPBs become a new LPB, which could combine with another LPB. The above process can be repeated until all the beamlets have been combined into one. It is obvious that the normalized intensity distribution of the combined beam is the same as that of the beamlets. And the beam quality of the resulting beam does not deteriorate while the power is amplified.

Assuming that the two orthogonal LPBs are a p-polarized light (P light) and an s-polarized light (S light) with amplitudes $A_{\rm p}$ and $A_{\rm s}$, respectively, the EPB could be formed by a polarization beam splitter (PBS). The orientation of the QWP's optical axes is decided by δ_0, $A_{\rm p}$, and $A_{\rm s}$. Under the conditions of $A_{\rm p} = A_{\rm s}$ and $\delta_0 \neq (2m+1)\frac{\pi}{2}$, the azimuth of the EPB's main axis is fixed at the angle bisector between S and P light, no matter what value of δ_0. This special case is adopted in this letter because it not only simplifies the theory but also is convenient for the orientation of QWPs in experiment. Moreover, identical intensity for all beams is more suitable to the actual situation.

According to the above discussion, a system configuration for combining N beams is shown schematically in Fig. 1. It includes a MOPA part and a polarized beam combination (PBC) part. The MOPA part is used to generate linearly polarized laser beams which are at the same frequency and phase locked. In the MOPA part, a seed beam outputted from a master oscillator with good beam quality is firstly collimated by a collimating lens. Subsequently it is polarized to a P light by a polarizer and split into N beamlets with equal power. All the beamlets are amplified and only half of them have their polarizations rotated by 90°. All amplifiers are the same and work in

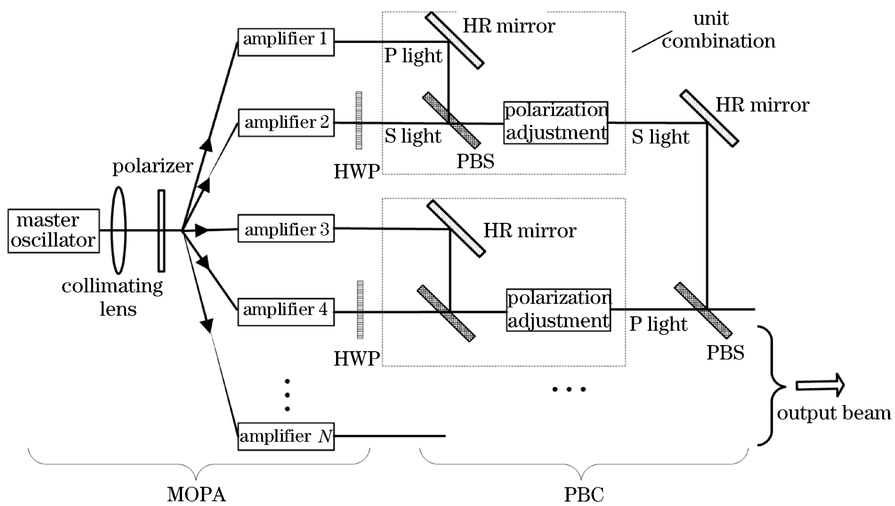

Fig. 1. Structure diagram of polarized beam combination system. HR: high reflectivity.

the cooling condition for reducing wave front differences among the beamlets caused by thermal effect. The collimating lens is used to change spherical wave front into plane one to eliminate the influence of radial phase factor of Gaussian beam on the combination efficiency. In the PBC part, all beams are coaxially superposed to an output beam eventually. The polarization adjustment module includes a QWP and a HWP. The system can also be exploited for multi-longitudinal-mode polarized beam combination by controlling the optical difference between the P and S light in each unit combination.

To analyze the amplifying ability of the system shown in Fig. 1, a unit combination is defined as the following process. Combine a P light and an S light into an EPB by a PBS and then convert it into a P light or an S light (the dotted frames in Fig. 1). The combining efficiency $\eta_{\rm u}$ of unit combination is defined as the intensity ratio of the combined P or S light to the sum of P and S light irradiated into PBS. The PBC part is made up of $N-2$ unit combinations when the final output is an EPB. For convenience, N is assumed to be even and written as $\sum_{i=1}^{n} 2^{m_i}$, where n and m_i are positive integers and $m_i > m_{i+1}$ (for example, $N = 22 = 2^4 + 2^2 + 2^1$, so $n = 3$ and $m_1 = 4$, $m_2 = 2$, $m_3 = 1$). When the intensity of each beam is I_0 and $\eta_{\rm u}$ is identical for all unit combinations, the relative output intensity (multiple of I_0) of the system is

$$I_{\rm r} = \begin{cases} 2^{m_n}\eta_{\rm u}^{m_n+n-2} + \sum\limits_{i=1}^{n-1} 2^{m_i}\eta_{\rm u}^{m_i+i-1} & (n>1) \\ 2^{m_1}\eta_{\rm u}^{m_1-1} & (n=1) \end{cases} . \quad (1)$$

From Eq. (1), for a given N, $I_{\rm r}$ increases with $\eta_{\rm u}$ when $\eta_{\rm u}$ is greater than 0.5. The relationship between $I_{\rm r}$ and N for different $\eta_{\rm u}$ is shown in Fig. 2. It can be seen that $I_{\rm r}$ at $N = 2^{m_i}$ is greater than that at $N = 2^{m_i} + \Delta N$, where ΔN is a small value. This is because the ΔN beams make the 2^{m_i} beams do another unit combination, but the power of the ΔN beams is smaller than the losses produced in the additional unit combination for all beams. The results in Fig. 2 illustrate that $\eta_{\rm u}$ has an important influence on $I_{\rm r}$. Therefore, $\eta_{\rm u}$ is the core problem in PBC.

$\eta_{\rm u}$ is the product of two parameters T and $\eta_{\rm pc}$, the transmittance T denotes the reflection and transmission loss of all optical components in a unit combination, and the polarization conversion efficiency $\eta_{\rm pc}$ means the ability of converting an EPB into a P light or an S light. In theory, $\eta_{\rm pc}$ is equal to 1 in the condition of single polarization state. However, it is more realistic that $\eta_{\rm pc}$ is smaller than 1 due to the following two factors. Firstly, due to the different surface shapes of optical elements and the parallelism error between S and P light, phase difference and polarization states are different at each point on the cross section of the combined beam. This case is called as non-uniform polarization. The parallelism error is the main influence factor in this case. Secondly, due to the environmental factors such as ambient vibration, temperature change, air flow, and mechanical stability, neither the phase difference between the S and P light nor the polarization state of the combined beam can be locked. When the environmental factors make the optical path difference between the P and S light change δz, for the case of $A_{\rm p} = A_{\rm s}$, $\eta_{\rm pc}$ can be expressed as

$$\eta_{\rm pc}(\delta z) = k\cos^2(\omega\delta z/2c), \quad (2)$$

where δz is a real-time random variable, c is the light speed in vacuum, ω is angular frequency, k is a coefficient determined by optical components and experimental operation. In a unit combination, if the polarization degree of the beam propagating through the QWP is p, then $k = (1+p)/2$. $(1-k)$ represents the relative loss caused by non-uniform polarization while $\cos^2(\omega\delta z/2c)$ denotes the effect of environmental factors.

An experiment of combining four beams by two unit combinations was carried out. The experimental setup is shown in Fig. 3. Compared with Fig. 1, no amplifier is used in the setup. However, there is no effect on verifying the feasibility of the PBC method. A He-Ne laser with two orthogonally longitudinal modes was used as a master oscillator. A single longitudinal mode was thus selected by a polarizer. The HWP behind the polarizer was used to make the intensity of beams split by PBS0 equal.

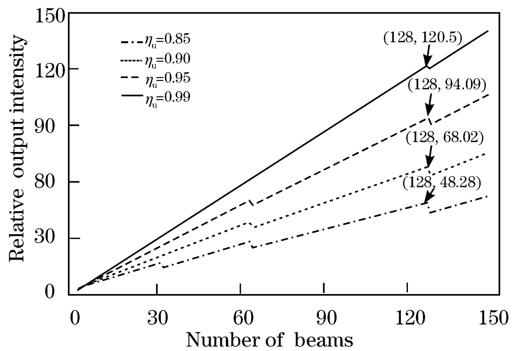

Fig. 2. Relationship between relative output intensity (multiple of I_0) and the number of beamlets for different η_u.

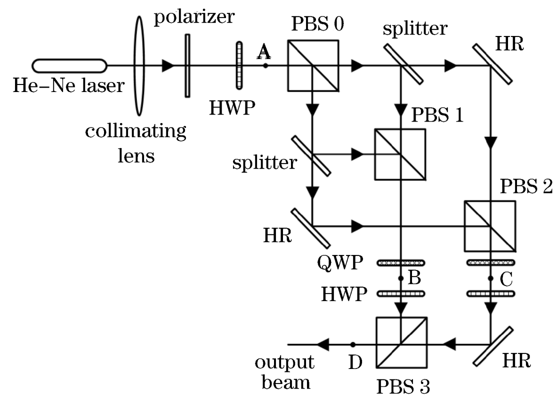

Fig. 3. Experimental setup for combining four beams.

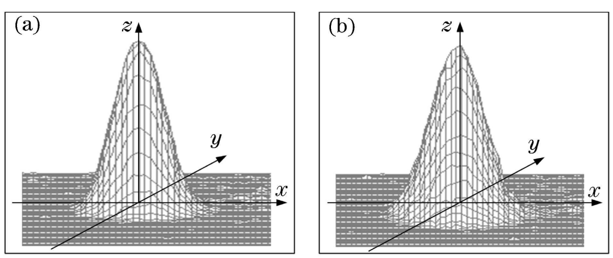

Fig. 4. 3D intensity distribution graphs measured by a beam quality analyzer. (a) Initial beam outputted from the He-Ne laser and (b) the combined beam.

In each unit combination, the following method was used to judge whether two beams were coaxially combined properly by a PBS. A polarizer whose polarization axis was not parallel to P and S light was inserted into the combined beam; it was considered as coaxial combination if no interference fringe was observed behind the polarizer.

A power meter with the uncertainty of 5% was used to measure the intensity. In the first unit combination which included PBS1, the values of T, p at the point B, and η_{pc} were 95.3%, 85.2%, and 89.9%, respectively. From the above parameters, we can get that η_u is 85.7%. In the second unit combination containing PBS2, the values of T, p at the point C, η_{pc}, and η_u were 95.1%, 83.3%, 88.3%, and 84.0%, respectively. Average combination efficiency of the system (intensity ratio at the point D to the point A) was 85.3% in 5 min. The relative losses caused by transmittance and reflection of components, non-uniform polarization, and environmental factors were 4.7%, 7.4%, 2.9% in the first unit combination and 4.9%, 8.4%, 3.7% in the second one.

The three-dimensional (3D) intensity graphs of the initial beam and the combined beam measured by a beam quality analyzer (BeamView of Coherent Inc.) are shown in Figs. 4(a) and (b), respectively. It is evident that the two intensity distributions are similar to each other, so the beam quality of the combined beam does not deteriorate compared with the initial light.

It should be noted that the combination efficiency of unit combinations and the system can be further improved through enhancing the quality of optical and mechanical components and improving the stability of experimental environment. For instance, when the transmittance T is raised to 98% in the first unit combination, about 2.4 percentage points are improved for η_u. In addition, a 3D adjusting mount with high precision is proposed to improve the consistency of wave fronts and combination efficiency. If the precision of the 3D adjusting mount is increased by a factor of 2, the combination efficiency of unit combination of more than 95% could be obtained.

In conclusion, we present a coaxial combining system based on MOPA structure. An experiment was performed to combine four beams into one. Combination efficiencies of unit combination and system were about 84%−86% and 85%, respectively. The beam quality of the combined beam does not deteriorate compared with the initial light. The combination efficiency could be further improved by making some progresses such as improving the quality of optical and mechanical components and the stability of experimental environment. The method could be applied in multi-longitudinal-mode beam combination.

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