Comparative study on the power scaling performance of three different coherent polarization beam combination system structures

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Coherent polarization beam combination (CPBC) is a new kind of coherent beam combination configuration with high combining efficiency and excellent beam quality. In order to extend the CPBC system to a large scale, we provide a comparative study on the power scaling performance of three different coherent polarization beam combination system structures. It is found that the pairwise structure has high tolerance to aberrations and has a potential to extend to a large scale with high combining efficiency. In consideration of all the aberrations, the combining efficiency of the pairwise structure can be reached as high as 90% when the combined beams are more than 200. Some instructive suggestions are given to extend the CPBC system to a large scale.

Keywords: coherent beam combination, polarization beam combination, aberrations

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1. Introduction

High power narrow line-width fiber lasers with good beam quality have significant potential applications in many fields, including nonlinear frequency conversion, gravitational wave detection, and remote sensing.[1] However, owing to the limitations of thermal load, nonlinear effects, and fiber damage, the output power of a narrow line-width fiber amplifier is limited.[2,3] Coherent beam combination (CBC) of several laser elements provides a feasible way to fulfill high laser power with good beam quality.[4−16] Conventional CBC structure includes several tiled beamlets, which inevitably induces beam quality degradation due to the sidelobes.[5−15] For the sake of avoiding the negative effect of common CBC structure, coherent polarization beam combination (CPBC) was proposed and all the laser beams are coaxially combined,[17,18] which has great potential to scale high power with good beam quality.

The four-channel CPBC system had been successfully demonstrated by Uberna *et al.*[17,18] When extended to a large scale, some aberrations in the CPBC system should be considered, such as the power loss of the polarization beam combiner (PBC), the overlap error (the beams in the polarization beam combiner cannot be superposed entirely due to the precision of the adjustment stand and assembling), the tilt error (the direction of the fiber laser beams cannot be exactly vertical due to the precision of the adjustment stand and assembling), and the phase error (phase differences between beams due to the performance of the phase compensating system). Due to the influence of those aberrations, the combining efficiency will decrease with the increase of the combined channels.

Up to now, three different structures have been proposed to extend the CPBC system. However, the feasibility of scaling CPBC to a large number of laser beams had not yet been investigated in detail. In this paper, three models for CPBC of multi-channel fiber lasers are established, the analytical expression of the output power and the combining efficiency of the system are obtained. By numerical analysis and comparison, the optimal configuration is selected for the multi-channel CPBC system. We also present some constructive suggestions to improve the system performance at the end of this paper.

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2. Theoretic analysis of models

The principle diagram of the multi-channel CPBC system is shown in Fig. 1. In the CPBC system, two polarized and phase-locked ($\phi_{12} = n_1\pi$, where n_1 is an integer) fiber laser beams whose polarization directions are perpendicular can be combined into a linearly polarized beam by a polarization beam combiner (PBC). By changing the polarization direction of the combined beam by rotating the half wavelength plate (HWP), it can be further coherently combined with a linearly polarized beam and combined into a linearly polarized beam through phase-locking ($\phi_{12,3} = n_2\pi$, where n_2 is an integer), so the multi-channel CPBC can be fulfilled.[15]

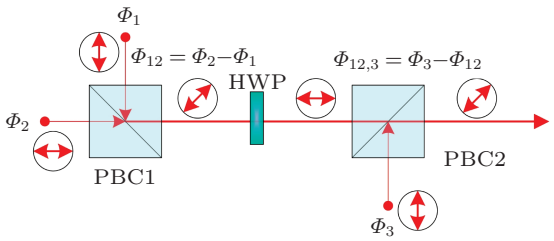


Fig. 1. (colour online) The principle diagram of the multi-channel CPBC system.

2.1. The basic unit of the CPBC system

Shown in Fig. 2 is the basic unit of the whole CPBC system. We firstly present a detailed study on this unit. Theoretically, the combined beam is pure linear-polarized without aberrations, which can be thoroughly transited to the next PBC by rotating the HWP and can be combined with another beam. However, a portion of power will leak to port1 and port2 due to the influence of the aberrations as mentioned above.

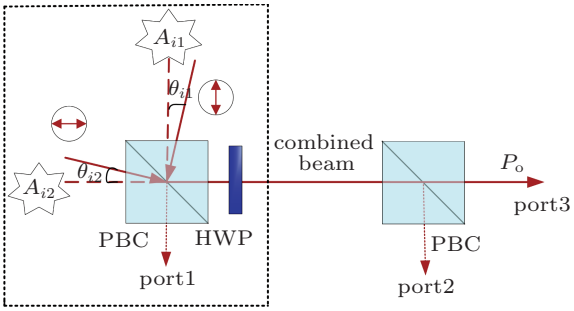


Fig. 2. (colour online) The principle diagram of one unit of the CPBC system.

Suppose that the complex amplitude field of each beam obeys Gaussian distribution, the combining efficiency η_{eff} of the unit can be expressed as

$$\eta_{\text{eff}} = \frac{P_{\text{o max}}}{P_{\text{ideal}}}. \tag{1}$$

The expression for P_{ideal} and $P_{\text{o max}}$ can be expressed as follows:

$$P_{\text{ideal}} = (A_{i1}^2 + A_{i2}^2) \times \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \exp\left(-\frac{2(x^2+y^2)}{\omega^2}\right) \mathrm{d}x\mathrm{d}y, \tag{2}$$

$$P_{\text{o max}} = \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \psi(x,y)\,\mathrm{d}x\mathrm{d}y + \frac{1}{2}\frac{\chi_2^2}{\sqrt{\chi_2^2 + \chi_1^2\cos^2\delta_i}} + \frac{1}{2}\frac{\chi_1^2\cos^2\delta_i}{\sqrt{\chi_2^2 + \beta_1^2\cos^2\delta_i}}, \tag{3}$$

where P_{ideal} is the output power of the unit of coherently polarization combined beam with no aberrations, $P_{\text{o max}}$ is the maximum output power in port3 through rotating the HWP in the case of aberrations.

$$\psi(x,y) = A_{i1}^2\cos^2(\theta_{i1})\exp\left(-\frac{2\left[\left(x-\frac{a_i}{2}\right)^2 + \left(y-\frac{b_i}{2}\right)^2\right]}{\omega^2}\right) + A_{i2}^2\cos^2(\theta_{i2})\exp\left(-\frac{2\left[\left(x+\frac{a_i}{2}\right)^2 + \left(y+\frac{b_i}{2}\right)^2\right]}{\omega^2}\right), \tag{4}$$

$$\chi_1 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\psi(x,y)\sin 2\varphi(x,y)\,\mathrm{d}x\mathrm{d}y, \quad \chi_2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\psi(x,y)\cos 2\varphi(x,y)\,\mathrm{d}x\mathrm{d}y, \tag{5}$$

$$\tan\varphi(x,y) = \frac{A_{i2}\cos(\theta_{i2})}{A_{i1}\cos(\theta_{i1})}\exp\left[-\frac{2(a_i x + b_i y)}{\omega^2}\right], \tag{6}$$

where A_{i1} and A_{i2} are the amplitudes of each beamlet; θ_{i1} and θ_{i2} represent the tilt angles as denoted in Fig. 1; ω is the beam waist of the fiber laser beam; δ_i is the phase error of the unit, which is denoted using the RMS value; $(a_i/2,\ b_i/2)$ is the center of one fiber laser beam, and $(-a_i/2,\ -b_i/2)$ is the center of the other fiber laser beam in the PBC.

2.2. Models of the CPBC system

To extend the CPBC system to multi-channel, three structures are mainly used for the CPBC system, namely pairwise structure (Fig. 3(a)), R-cascade structure (Fig. 3(b)), and T-cascade structure (Fig. 3(c)). For simplicity, we leave out the master oscillator, the amplifier cascade, the collimators, and the feedback control module in the schematic of each model. Generally, the power loss in each PBC is denoted by varying the unit-combining efficiency. To analyze the effects of the aberrations quantitatively, the models assume that the combining efficiency of each PBC is identical and the power of each fiber beam from the collimator is identical, too. Note that the surface intensity reflectance of the PBC to optical fields is not 100%, the intensity reflectance of the PBC to ordinary optical field and the intensity transmittance of the PBC to extraordinary optical field are also not 100% in practice. The influences of these factors are also considered in the three structures.

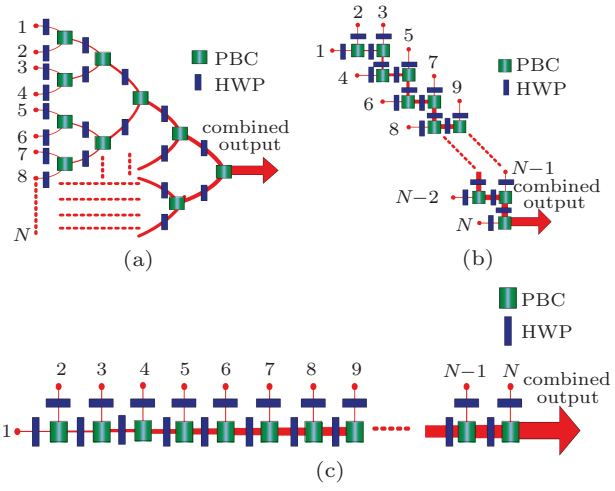


Fig. 3. (colour online) Schematic of the models of the CPBC system: (a) pairwise structure (b) R-cascade structure, and (c) T-cascade structure.

2.2.1. Pairwise structure

In the pairwise CPBC system, two linear-polarized beams are combined by using one PBC, then the laser beams are combined in cascading. Provided that the schematic of the model for a system contains k $(N = 2^k)$ stages, where N is the number of fiber laser beams injected into the combined stage.

In consideration of the effects of the aberrations, the coherently combined output power of this model can be written as

$$P_{\text{P-com}} = \left(\sum_{\mu=1}^{N} P_{2^k,\mu}\right)\eta_{\text{pairwise}}, \tag{7}$$

where $P_{\text{P}-\text{com}}$ is the combined output power of the pairwise structure, $P_{2^k,\mu}$ is the power of the μth-channel amplified fiber laser beam, and η_{pairwise} is the combining efficiency of the whole system.

By setting $P_{\text{com}} = P_{11}$, the relationship between two adjacent stages can be expressed as

$$\sum_{j=1}^{2^{n-1}} \frac{P_{2^{n-1},j}}{\eta_{2^{n-1},j}} = \sum_{m=1}^{2^n} P_{2^n,m}, \quad n = 1, 2, 3, \ldots, k, \tag{8}$$

where $P_{2^{n-1},j}$ is the j-th-channel power in the $(n-1)$-th stage, $\eta_{2^{n-1},j}$ is the combining efficiency of the PBC in the j-th-channel of the $(n-1)$-th stage, $P_{2^n,m}$ is the mth-channel power in the nth stage, which is in front of the $(n-1)$-th stage.

We can obtain that

$$\eta_{\text{pairwise}} = \left(\frac{R_{\text{s}} + T_{\text{p}}}{2}\right)^k R_{\text{f}}^k \eta_{\text{eff}}^k, \tag{9}$$

where R_{f} is the surface intensity reflectance of the PBC, R_{s} is the intensity reflectance of the PBC to ordinary optical field, T_{p} is the intensity transmittance of the PBC to extraordinary optical field, and η_{eff} is the combining efficiency of each PBC.

2.2.2. R-cascade structure

Taking the effects of the aberrations into account, the coherently combined output power of R-cascade model can be expressed as

$$P_{\text{Rcom}} = \left(\sum_{i=1}^{N} \text{P}_i\right)\eta_{\text{R-cascade}}, \tag{10}$$

where P_{Rcom} is the combined output power of the R-cascade structure, P_i is the power of the i-th-channel amplified fiber laser beam, $\eta_{\text{R-cascade}}$ is the combining efficiency of the R-cascade system, and N is the number of fiber laser beams injected into the combined stage. It reveals that when N beams combined, $(N-1)$ PBCs should be used in the system.

By setting $P_{\mathrm{Rcom}} = P_{\mathrm{com}(N-1)}$, $P_{\mathrm{com}0} = P_1$, the relationship between two adjacent stages can be expressed as

$$\frac{P_{\mathrm{com}i}}{\eta_i} = P_{i+1} + P_{\mathrm{com}(i-1)}, \quad i = 1, 2, 3, \ldots, N-1, \tag{11}$$

where $P_{\mathrm{com}i}$ is the combined output power of the i-th-PBC, and η_i is the combining efficiency of the i-th-PBC.

The R-cascade model assumes that the combining efficiency of each PBC is identical and the power of each amplified fiber beam is uniform.

We can obtain

$$\eta_{\text{R-cascade}} = \frac{-R_{\mathrm{f}}^N \eta_{\mathrm{eff}}^N R_{\mathrm{s}}^N + (1 - R_{\mathrm{f}}\eta_{\mathrm{eff}} T_{\mathrm{p}}) R_{\mathrm{f}}^{N-1} \eta_{\mathrm{eff}}^{N-1} R_{\mathrm{s}}^{N-1} + R_{\mathrm{f}} T_{\mathrm{p}} \eta_{\mathrm{eff}}}{N(1 - R_{\mathrm{f}}\eta_{\mathrm{eff}} R_{\mathrm{s}})}, \quad (N \geq 2). \tag{12}$$

2.2.3. T-cascade structure

By taking the effect factors above into account, the coherently combined output power of the T-cascade model can be expressed as

$$P_{\mathrm{Tcom}} = \left(\sum_{\gamma=1}^{N} P_\gamma \right) \eta_{\text{T-cascade}}, \tag{13}$$

where P_{Tcom} is the combined output power of the T-cascade structure, P_γ is the power of the γth-channel amplified fiber laser beam, and $\eta_{\text{T-cascade}}$ is the combining efficiency of the T-cascade system. When N beams are combined, $(N-1)$ PBCs are also used in the system.

By setting $P_{\mathrm{Tcom}} = P_{\mathrm{com}(N-1)}$, $P_{\mathrm{com}0} = P_1$, the relationship between two adjacent stages can be also expressed as

$$\frac{P_{\mathrm{com}\gamma}}{\eta_\gamma} = P_{\gamma+1} + P_{\mathrm{com}(\gamma-1)}, \quad \gamma = 1, 2, 3, \ldots, N-1, \tag{14}$$

where $P_{\mathrm{com}\gamma}$ is the combined output power of the γ-th-PBC, and η_γ is the combining efficiency of the i-th-PBC.

The T-cascade model also assumes that the combining efficiency of each PBC is identical and the power of each amplified fiber beam is uniform.

We can obtain that

$$\eta_{\text{T-cascade}} = \frac{-R_{\mathrm{f}}^N \eta_{\mathrm{eff}}^N T_{\mathrm{p}}^N + (1 - R_{\mathrm{f}}\eta_{\mathrm{eff}} R_{\mathrm{s}}) R_{\mathrm{f}}^{N-1} \eta_{\mathrm{eff}}^{N-1} T_{\mathrm{p}}^{N-1} + R_{\mathrm{f}} R_{\mathrm{s}} \eta_{\mathrm{eff}}}{N(1 - R_{\mathrm{f}}\eta_{\mathrm{eff}} T_{\mathrm{p}})}, \quad (N \geq 2). \tag{15}$$

The models have been analyzed theoretically, which are related to the combining efficiency of the unit of CPBC system. Thus, the coherently polarization combined output power is obtained as a function of combining efficiency of the system for each model, which is related to the factors of the aberrations.

3. Simulation results and discussion

The relationship between the coherently combined output power and the combining efficiency of the CPBC system for each model has been deduced, which involves the effects of the PBCs, the overlap error, the tilt error, and the phase error. We numerically analyze the effects of these factors on the combining efficiency of each model, compare the tolerance of these aberrations for these three models and propose the optimal model of the CPBC system with some instructive suggestions to improve the system performance.

3.1. Effect of R_{f}

As aforementioned, the surface intensity reflectance (R_{f}) of the PBC is not 100% in practice, so we discuss the influence of R_{f} on the combining efficiency of the CPBC system in this section. By investigating the products of PBCs, we find that R_{f} is normally less than 99.5%. For simplicity, we suppose no other aberrations exist, so we choose $N = 32$, $\omega = 5$ mm, $a_i = b_i = 0$ mm, $\theta_{i1} = \theta_{i2} = 0$ rad, and $R_{\mathrm{s}} = T_{\mathrm{p}} = 100\%$, the RMS of the phase error $\delta_i = 0$ rad in the numerical simulations. The influence of R_{f} on the combining efficiency of the three structures are

depicted in Fig. 4.

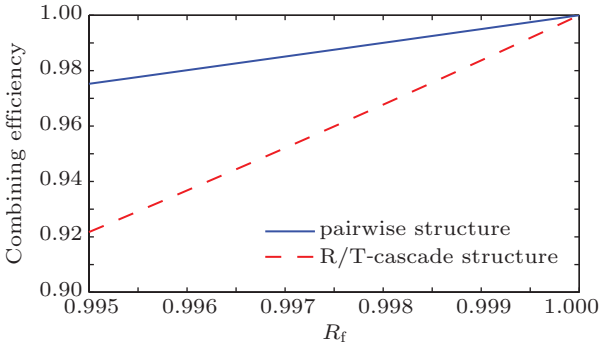


Fig. 4. (colour online) Combining efficiency as a function of R_f for different structures.

It shows that the combining efficiency decreases with the decrease of R_f. We also obtain that pairwise structure has higher tolerance to the influence of R_f than R-cascade structure and T-cascade structure. Note that when $R_s = T_p = 100\%$, the influences of the R_f on R-cascade structure and T-cascade structure are the same.

3.2. Effect of R_s and T_p

Due to the limitations of material and technique, the intensity reflectance of the PBC to ordinary optical field and the intensity transmittance of the PBC to extraordinary optical field are not 100% in practice, so it is significant to analyze the influence of the PBCs in the CPBC system. Generally, in terms of the PBC, R_s can be reached nearly 100%, while T_p is less than R_s. For simplicity, we suppose no other aberrations exist, so we choose $N = 32$, $\omega = 5$ mm, $a_i = b_i = 0$ nm, $\theta_{i1} = \theta_{i2} = 0$ rad, $R_f = 100\%$, and the RMS of the phase error $\delta_i = 0$ rad in the numerical simulations. The effects of the aberrations will be discussed in detail in the following sections.

From Eqs. (9), (12), and (15), we see that for a given T_p, a certain R_s' exists so that R-cascade structure will obtain higher combining efficiency when R_s is higher than R_s'; while for a given R_s, we conclude that a certain T_p' exists so that pairwise structure will obtain higher combining efficiency when T_p is higher than T_p'. The influences of R_s and T_p on the combining efficiency of the three structures are depicted in Figs. 5(a) and 5(b), respectively.

It is revealed that the combining efficiency decreases with the decrease of the R_s and T_p and the R-cascade structure is sensitive to the change of R_s while T-cascade structure is sensitive to the change of T_p. For the pairwise structure, the influences of R_s and T_p are equilibrial. Figure 5(a) shows that R-cascade structure will obtain higher combining efficiency when $T_p = 98\%$ and R_s is more than 98%, and the combining efficiency is more than 94%. Figure 5(b) shows that the pairwise structure will obtain higher combining efficiency when $R_s = 99.9\%$ and T_p is more than 98.5%, and the combining efficiency is more than 95%. For the T-cascade structure, note that the combining efficiency will be below 60% when $T_p = 98\%$, $R_s = 99.9\%$, and N is more than 56. Overall, it is found that the R-cascade structure and the pairwise structure has the potential to extend the CPBC system to a large scale and the influence of the PBCs should be taken into account in the option of structure and large scale CPBC system for power scaling.

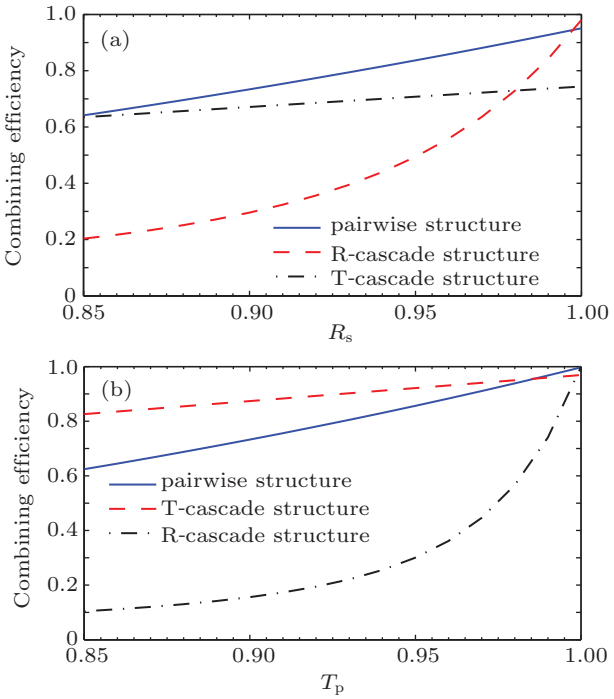


Fig. 5. (colour online) Combining efficiency as a function of R_s and T_p for different structures: (a) $T_p = 98\%$, $N = 32$; (b) $R_s = 99.9\%$, $N = 32$.

3.3. Effect of the overlap error

Due to the precision of the adjustment stand and assembling, the beams in the PBCs cannot be superposed entirely. By analyzing the model, we obtain that the overlap error ($a_i \neq 0$ and $b_i \neq 0$) affects the direction of the coherently polarization combined beam and the combining efficiency of the whole system. Considering the practical condition, we choose

$R_s = 99.9\%$, $T_p = 98\%$, $R_f = 99.8\%$, and the other parameters are identical to that in Fig. 5. We define $d_i = \sqrt{a_i^2 + b_i^2}$, and using normalized ratio a_i/ω, b_i/ω, and d_i/ω to denote the magnitude of the overlap error. We analyze the effects of the overlap error with different structures, the results are given in Fig. 6.

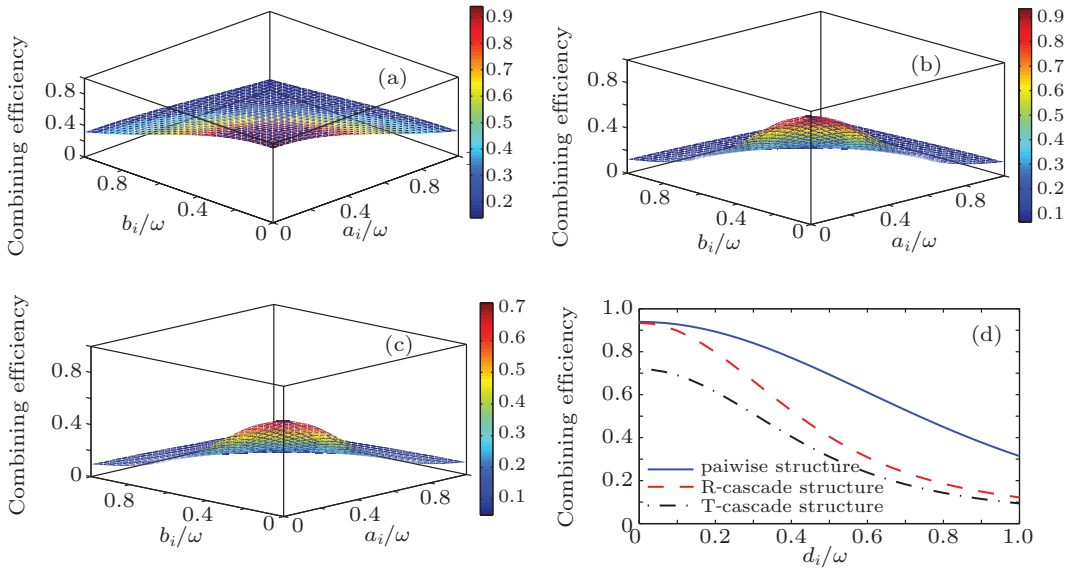


Fig. 6. (colour online) Combining efficiency as a function of the normalized overlap error for different structures: (a) pairwise structure, (b) R-cascade structure, (c) T-cascade structure, (d) two-dimensional function.

It is shown that the R-cascade structure and the T-cascade structure are more vulnerable to the increase of the overlap error. Specifically, when $d_i/\omega = 0.5$, the combining efficiency will change from 93.9%, 93.4%, and 71.9% to 69.4%, 40.4%, and 31.1% for the pairwise structure, the R-cascade structure, and the T-cascade structure, respectively. In the simulation, for the pairwise structure and the R-cascade structure, to ensure the combining efficiency is more than 90%, the overlap error d_i/ω should be less than 0.17 and 0.1, respectively. We can conclude that the combining efficiency of the system is sensitive to the overlap error, so in a large-scale system, the high precision adjustment mounts and trestle tables are necessary.

3.4. Effect of the tilt error

Due to the limitation of the precision of the adjustment stand and assembling, the axis of lasers in the PBC cannot be strictly vertical. In previous theoretical analysis, the tilt errors have been taken into account. We choose $R_s = 99.9\%$, $T_p = 98\%$, $R_f = 99.8\%$, $\omega = 5$ mm, $a_i = b_i = 0$ mm, $\delta_i = 0$ rad, and $N = 32$. The dependence of the combining efficiency on the tilt errors with different structures are given in Fig. 7. It also reveals that the R-cascade structure and the T-cascade structure are more sensitive to the increase of the tilt error. In particular, when $\theta_{i1} = \theta_{i2} = 0$ rad, the combining efficiency are 93.9%, 93.4%, and 71.9% while $\theta_{i1} = \theta_{i2} = \pi/15$ rad, the combining efficiency are 75.3%, 49.3%, and 38.0% for the pairwise structure, the R-cascade structure, and the T-cascade structure, respectively. For the pairwise structure and the R-cascade structure, to ensure the combining efficiency is more than 90%, the tilt error should be less than $\pi/35$ rad and $\pi/65$ rad, respectively. Generally, the combining efficiency is vulnerable to the tilt error, so in a large-scale CPBC system, the tilt error should also be taken into consideration.

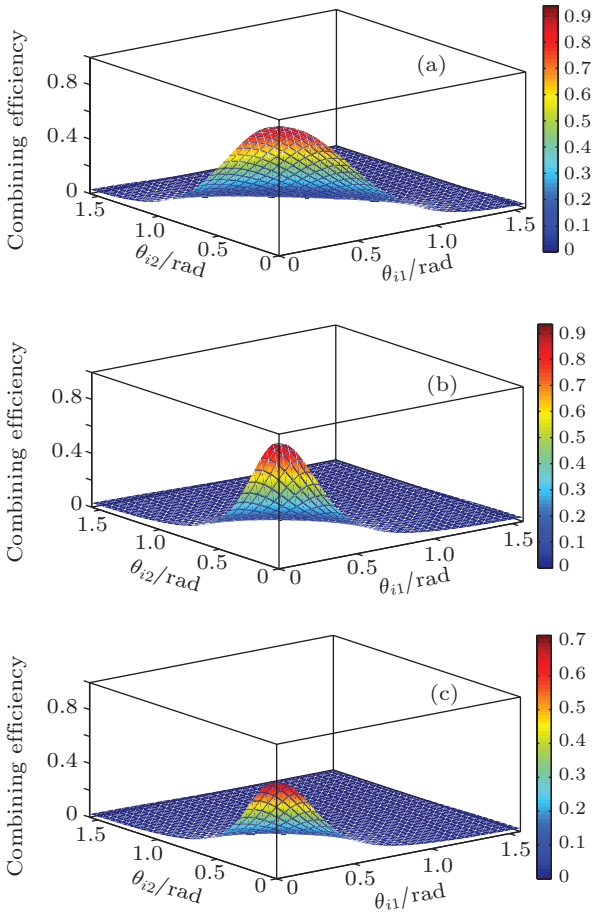


Fig. 7. (colour online) Combining efficiency as a function of the tilt error for different structures: (a) pairwise structure, (b) R-cascade structure, (c) T-cascade structure.

3.5. Effect of the phase error

Due to the influence of the factors like thermal effects in fibers, the mechanical dithering, experimental environment and so forth, the control module of phase locking cannot compensate the relative phase difference among channels to be zeros all the time. In fact, the relative phase difference among channels fluctuates all the time. The phase error will induce the change of the polarization of the coherently combined beam and the decrease of the combining efficiency of the system. We use the RMS value δ_i to denote the phase error at the i-th PBC and choose $R_s = 99.9\%$, $T_p = 98\%$, $R_f = 99.8\%$, $\omega = 5$ mm, $N = 32$, $a_i = b_i = 0$ mm, and $\theta_{i1} = \theta_{i2} = 0$ rad in the numerical simulation. The results are shown in Fig. 8.

It shows that the combining efficiency decreases as the phase error increases for the three structures. Relatively, the pairwise structure has higher tolerance of the phase error compared with the R-cascade structure and the T-cascade structure. The phase error with $\lambda/60$ RMS value will cause that the combining efficiency decreases from 93.9%, 93.4%, and 71.9% to 92.6%, 89.4%, and 68.8% for the pairwise structure, the R-cascade structure, and the T-structure, respectively. For the pairwise structure and the R-cascade structure, to ensure the combining efficiency is more than 90%, the phase error must be controlled to be within $\lambda/33$ and $\lambda/57$. The phase error within $\lambda/50$ has been demonstrated in Ref. [19], so the influence of phase error on the CPBC system can be lower when N is less than 32.

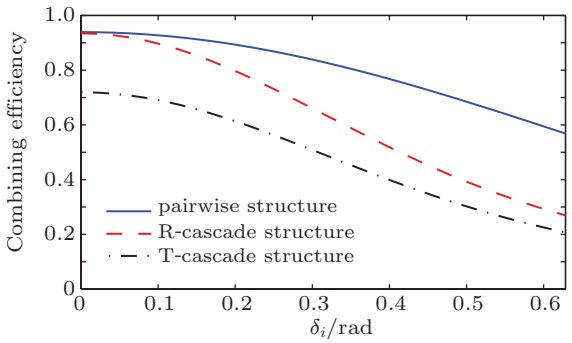


Fig. 8. (colour online) Combining efficiency as a function of the phase error for different structures.

4. Extensibility and discussion

To scale high output power using the CPBC system, the analysis of the extensibility of the system is crucial and necessary. We analyze the effects of aberrations on a multi-channel system. In the numerical simulation, we choose $\omega = 5$ mm, $R_s = 99.9\%$, $T_p = 98\%$, and $R_f = 99.8\%$. The results are shown in Fig. 9. In Fig. 9(a), we suppose no aberrations exist, the combining efficiency and extensibility of the system are only restricted to R_f, R_s, and T_p. The combining efficiency decreases with the increase of the coherently polarization combined beams. For $N = 256$, it is shown that the combining efficiency is 90.4%, 67.7%, and 15.2% for the pairwise structure, the R-cascade structure, and the T-cascade structure, respectively. It reveals that if other aberrations are compensated effectively, the CPBC system can be extended to a large scale using the pairwise structure. In Fig. 9(b), supposing that the combining efficiency and extensibility of the system are confined to R_f, R_s, T_p, and the overlap error and we choose $a_i = b_i = \omega/10$ (mm). For a given N, for example $N = 256$, the combining efficiency is 87%, 40.1%, and 9% for the pairwise structure, the R-cascade structure, and the T-cascade

structure, respectively. In Fig. 9(c), the combining efficiency and extensibility of the system are constrained to $R_{\rm f}$, $R_{\rm s}$, $T_{\rm p}$, and the tilt error, and we assume $\theta_{i1} = \theta_{i2} = \pi/60$ rad. For a given N, for example $N = 256$, the combining efficiency is 88.5%, 50.1%, and 11.2% for the pairwise structure, the R-cascade structure, and the T-cascade structure, respectively. In Fig. 9(d), the combining efficiency and extensibility of the system are affected by $R_{\rm f}$, $R_{\rm s}$, $T_{\rm p}$, and the phase error, and we presume $\delta_i = \lambda/60$. For $N = 256$, the combining efficiency is 88.5%, 50.1%, and 11.2% for the pairwise structure, the R-cascade structure, and the T-cascade structure, respectively.

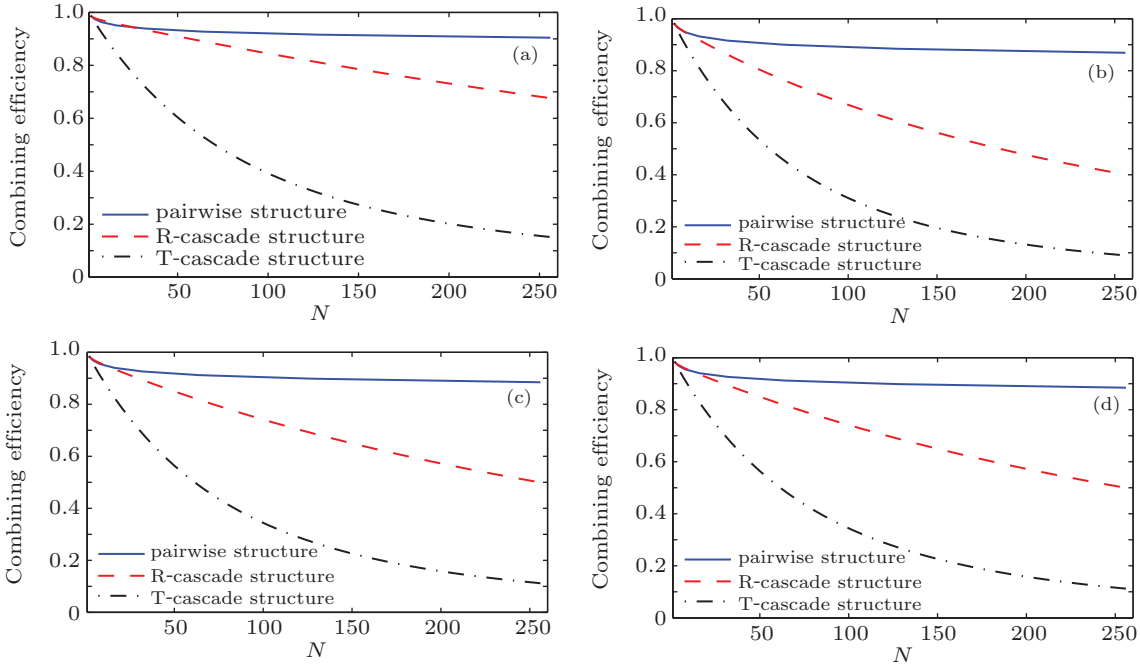


Fig. 9. (colour online) Combining efficiency as a function of N for different structures with (a) no aberrations, (b) overlap errors ($a_i = b_i = \omega/10$ (mm)), (c) tilt errors ($\theta_{i1} = \theta_{i2} = \pi/60$ (rad)), and (d) phase errors ($\delta_i = \lambda/60$).

Through analysis of the extensibility of the system and the effects of the aberrations on the combining efficiency of the system, we find that the pairwise structure has a higher tolerance to the overlap error, the tilt error, the phase error, and the influence of the PBCs in multi-channel CPBC system than the other two structures, which has a great potential in scaling to high power with good beam quality.

5. Conclusion

In summary, three models of the CPBC system are developed, the effects of the PBCs, the overlap error, the tilt error and the phase error on the combining efficiency and extensibility of the system are studied. We find that the PBCs, the overlap error, the tilt error, and the phase error are sensitive to the combining efficiency of the system. It is found that the pairwise structure has high tolerance to aberrations and the effects of the PBCs, which has a potential to extend the CPBC system to a large scale with high combining efficiency. The conclusions we made are important in extending the CPBC system. The methodology we proposed offers a good reference for analyzing CPBC system in a comprehensive way.

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