Effect of coupling strength on the phase locking performance of fiber lasers coupled with a common ring cavity

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Abstract: Passive phase locking of two fiber lasers which were coupled by a common ring cavity had been demonstrated, and the effect of coupling strength between them on the phase locking performance had been investigated in detail. The ring coupled cavity was chiefly composed of two 2×2 fiber couplers, which provided a common channel for mutual injection coupling and made the output phases of component lasers were primarily synchronized. The theoretical model of analyzing the effect of coupling strength was presented, which was based on the fact that the coupling strength between the fiber lasers was mainly determined by the coupling ratios of fiber couplers, and the effect of magnitude and difference of these coupling ratios on the circulating intensity in the common ring cavity and the output intensity of the phase locking array were investigated in theory. Moreover, efficient phase locking of two Erbium-doped fiber lasers with the common ring coupled cavity had been demonstrated, and the coherence of output lasers and their combining efficiency were also studied by analyzing the far-field interference pattern and output power of the array in experiment. The research results indicatd that adequate coupling strength was a necessary condition to achieve effective phase locking, and improving the coupling strength by increasing the coupling ratio can enhance the coherence of the phase locking array and decrease the combining efficiency slightly.

Key words: fiber lasers; phase locking; mutual injection coupling; ring coupled cavity; coupling strength

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耦合强度对公共环形腔耦合式光纤激光器锁相性能的影响

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摘 要: 利用公共环形腔耦合实现了两路光纤激光器的无源相位锁定, 研究了激光器之间耦合强度对锁相性能的影响。环形耦合腔主要由两个 2×2 的光纤耦合器组成,其构成了激光器之间能量相互注入耦合的公共通道,并使它们获得了初步的相位同步。考虑到耦合强度主要由成环光纤耦合器的耦合比决定,建立了分析耦合强度影响的理论模型,并从理论上研究了耦合比的大小和差异对环内光强和输出光强的影响。此外,实验上实现了两路掺铒光纤激光器的有效相位锁定,并通过分析远场干涉光斑和输出功率研究了锁相阵列输出激光束的相干性和合成效率。研究结果表明:足够的能量耦合强度是获得有效相位锁定的必要条件,通过增加耦合比来增大耦合强度可以提高锁相阵列的相干性,但会略微降低合成效率。

关键词: 光纤激光器; 相位锁定; 相互注入耦合; 环形耦合腔; 耦合强度

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0 Introduction

The laser source with high brightness and high average power has wide-ranging applications in many fields, and coherent beam combining of multiple fiber lasers in a phased array has been expected to be an effective way to obtain a laser source of this kind[1-3]. The active phase controlling techniques can adjust the phase errors precisely and gain outstanding combining effects, but they require complicated phase detection and correction measures for each element of the array, and their costs are usually high[4-7]. The passive self-adjusting methods are relatively simple and easy to implement, but they often need tight optical coupling to obtain mutual coherence[8-15]. How to obtain proper optical coupling among component fiber lasers, and how the optical coupling affect the phase locking performance of a coupled laser array, are the key problems in the current coherent combining fields[16-18].

In this paper, passive phase locking of two Erbium-doped fiber lasers based on a common ring coupled cavity and single-mode fiber filtering technique has been demonstrated. Thanks to the special designed ring coupled cavity, the necessary optical coupling is introduced among component fiber lasers and primary phase synchronization is obtained, and a single-mode feedback fiber is introduced simultaneously to filter the far-field pattern to achieve a stable phase locking state. The effect of coupling strength between the two fiber lasers on the array´s phase locking performance has been investigated both in theory and experiment, and the coherence of output lasers and their combining efficiency are studied by analyzing the phase locking array′s far-field interference pattern and output power, and the experimental results are basically agree with the theoretical analysis. The research results indicate that it is necessary to bring adequate coupling strength to achieve effective phase locking, and improving the coupling strength by increasing the coupling ratio can ameliorate the coherence of the phase locking array and decrease the combining efficiency slightly, and small coupling ratio difference among component fiber lasers has very little effect on the phase locking performance.

1 Experimental setup

The experimental setup is schematically presented in Fig. 1. Both the component fiber lasers employ the typical linear resonator, which is formed by a fiber Bragg grating (FBG) and 4% Fresnel reflection at the perpendicularly cleaved facet of output fiber collimator (FC). The FBGs′ Bragg center wavelengths are close to 1550nm. The gain fibers are single-mode Erbium-doped fibers (EDF), and their lengths are 11.5 m and 10 m, respectively. The EDF is pumped by 980 nm laser diode (LD) through the 980/1550 wavelength division multiplexer (WDM). Two 2×2 polarization insensitive fiber couplers (PIFC) are inserted into their linear resonators between the FBG and gain fiber. The 80% ports remain in their linear resonator, whereas the rest 20% ports, together with a 2×1 fiber combiner and an optical isolator (OI), are connected to each other to form a common ring coupled cavity. Two fiber collimators are utilized to transform the output lasers to quasi-parallel beams with larger sizes, which is helpful for increasing the filling factor. A beam splitter (BS) is placed at the output ends of FCs, and nearly 4% output power is reflected and sent to positive lens L_1. This lens performs a Fourier transform from its front focal plane where FCs locates to its back focal plane, where a single-mode feedback fiber (SMFF, Corning SMF-28) is set to filter the spatial frequency spectrum. Another positive lens L_2 with a focal length of 40 cm is employed to converge

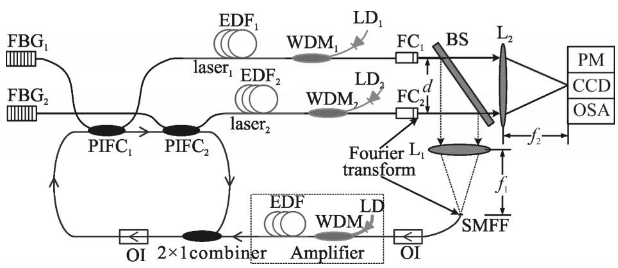

Fig.1 Experimental setup of two fiber lasers phase locking array with a common ring coupled cavity

the parallel output beams, and the power meter (PM), infrared CCD and optical spectrum analyzer (OSA) are placed at its back focal plane to study the coherent output properties.

To obtain the best filtering and highest feedback coupling efficiency, the mode field diameter of the SMFF needs to be slightly smaller than the central lobe size of the in-phase mode. In our experimental setup, the focal length of L_1 is 80 mm, and the spacing of the FCs (i.e. d) is nearly 8 mm, and thus the central lobe size of the in-phase mode is $\varphi=\lambda f_1/d\approx 15.5$ μm. Moreover, a self-made fiber amplifier is included into the feedback loop to amplify the feedback power to a proper value.

2 Theoretical analysis of the ring coupled cavity

The ring coupled cavity is the pivotal component of the phase locking array, and its characteristics have important effect on the performance of the phase locking array. On one hand, the energy coupled into the common ring cavity needs to be strong enough to obtain efficient mutual injection coupling among component lasers; on the other hand, most of the energy coupled into the common ring cavity needs to be coupled out from output ports in order to achieve higher combining efficiency. According to the research results in Ref. [19], we believe that it is reasonable to choose the intensity addition method to analyze the properties of the ring cavity since the bandwidth of input lightwave is not narrow enough and no obvious resonant peaks emerge from the ring cavity. According to the experimental configuration shown in Fig.1, a ring coupled cavity mainly constructed by two fiber couplers can be obtained and shown in Fig.2, which is the model used to analyze the properties of the ring coupled cavity, and the couplers C_1 and C_2 are corresponding to PIF C_1 and PIFC_2 shown in Fig.1.

Denoting the coupling ratio and the insertion loss of fiber coupler C_1 and C_2 as k_1, k_2, γ_1, γ_2, and denoting the splice intensity loss, the fiber transmission loss per unit

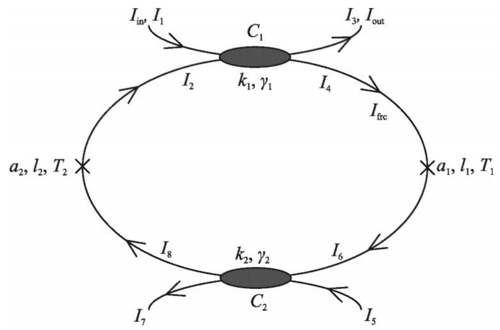

Fig.2 Model used to analyze the properties of the ring coupled cavity

length, and the fiber length between C_1 and C_2 as α_1, α_2, α_0, l_1, l_2, thus the power transmission coefficient taking its loss into account is $T_i=(1-\alpha_i)\exp(-\alpha_0 l_i)$, $i=1, 2$. Supposing the input intensity of the ring cavity is I_1, the output intensity experienced multiple transmissions is I_3, and the circulating intensity in the ring cavity is I_4, thus I_3 and I_4 can be given as

$$\begin{aligned}I_3=&I_1(1-k_1)(1-\gamma_1)+I_1k_1^2(1-\gamma_1)^2T_1(1-k_2)(1-\gamma_2)T_2+\\&I_1k_1^2(1-\gamma_1)^2(1-k_1)(1-\gamma_1)T_1^2[(1-k_2)(1-\gamma_2)^2]T_2^2+\cdots+\\&I_5k_2(1-\gamma_2)T_2k_1(1-\gamma_1)+I_5k_2(1-\gamma_2)T_2(1-k_1)(1-\gamma_1)\\&T_1(1-k_2)(1-\gamma_2)T_2k_1(1-\gamma_1)+\cdots\\I_4=&I_1k_1(1-\gamma_1)+I_1k_1(1-k_1)(1-\gamma_1)^2T_1(1-k_2)(1-\gamma_2)T_2+\\&I_1k_2(1-k_1)^2(1-\gamma_1)^3T_1^2[(1-k_2)(1-\gamma_2)^2]T_2^2+\cdots+\\&I_5k_2(1-\gamma_2)T_2(1-k_1)(1-\gamma_1)+I_5k_2(1-\gamma_2)T_2[(1-k_1)\\&(1-\gamma_1)^2]T_1(1-k_2)(1-\gamma_2)T_2+\cdots\end{aligned}\tag{1}$$

For the purpose of simplicity and without losing the universality, we assume the insertion loss, the power transmission coefficient and the input intensity of fiber coupler C_1 and C_2 are equal, i.e. $\gamma_1=\gamma_2=\gamma_0$, $T_1=T_2=T_0$, $I_1=I_5=I_{in}$, and then Eq.(1) can be rewritten as

$$\begin{aligned}\frac{I_3}{I_{in}}=&(1-k_1)(1-\gamma_0)+k_1(1-\gamma_0)^2T_0\\&\left[\frac{k_2+k_1(1-k_2)(1-\gamma_0)T_0}{1-(1-k_1)(1-k_2)(1-\gamma_0)^2T_0^2}\right]\\\frac{I_4}{I_{in}}=&(1-\gamma_0)\left[\frac{k_1+k_2(1-k_1)(1-\gamma_0)T_0}{1-(1-k_1)(1-k_2)(1-\gamma_0)^2T_0^2}\right]\end{aligned}\tag{2}$$

To describe the phase locking properties conveniently, we have defined two parameters, the combining efficiency η and the coupling coefficient κ, which are expressed as

$$\eta=\frac{I_3+I_7}{I_1+I_5}=\frac{I_3+I_7}{2I_{in}}\tag{3}$$

$$\kappa=\frac{I_4+I_8}{I_1+I_5}=\frac{I_4+I_8}{2I_{in}}=\frac{I_{frc}}{I_{in}} \tag{4}$$

Where I_{frc} means the average intensity in the fiber ring cavity, it is equal to $\frac{1}{2}(I_4+I_8)$ in the situation mentioned in Fig.2. When the coupling ratio of C_1 and C_2 is equal, i.e. $k_1=k_2=k$, the output intensity from the two ports of the ring cavity is also equal due to its symmetry, and then we can rewrite the combining efficiency η and the coupling coefficient κ as

$$\eta=\frac{(1-k)(1-\gamma_0)-(1-2k)(1-\gamma_0)^2T_0}{1-(1-k)(1-\gamma_0)T_0}$$

$$\kappa=\frac{k(1-\gamma_0)}{1-(1-k)(1-\gamma_0)T_0} \tag{5}$$

When the coupling ratio of C_1 and C_2 is not equal, i.e. $k_1\neq k_2$, we can find that the output intensity from the two ports of the ring cavity is also not equal, and then the Eqs. (3) and (4) can be rewritten as

$$\eta=\frac{1-\gamma_0}{2}\left\{2-\frac{[1-(1-\gamma_0)T_0][k_1+k_2+(k_1+k_2-2k_1k_2)(1-\gamma_0)T_0]}{1-(1-k_1)(1-k_2)(1-\gamma_0)^2T_0^2}\right\}$$

$$\kappa=\frac{1-\gamma_0}{2}\left[\frac{k_1+k_2+(k_1+k_2-2k_1k_2)(1-\gamma_0)T_0}{1-(1-k_1)(1-k_2)(1-\gamma_0)^2T_0^2}\right] \tag{6}$$

3 Results and discussion

Based on the experimental setup and analyzing model provided above, both the experimental and numerical results will be given and compared in this section, and the effects of coupling strength on the arrays′ phase locking performance are investigated by altering the fiber couplers′ coupling ratio. The phase locking performance is chiefly represented by the combining efficiency, interference pattern′s fringe visibility and its stability, and the coupling strength between two fiber lasers is mainly determined by the coupling ratio. According to whether the fiber couplers′ coupling ratios are equal or not, symmetrical coupling with the same coupling ratio and unsymmetrical coupling with different coupling ratios are researched respectively.

3.1 Phase locking with symmetrical coupling

Since the ring coupled cavity and SMFF are introduced into the two fiber lasers array, obvious and stable phase locking states are observed in experiment. The far field interference patterns are recorded by an infrared CCD (Electrophysics, 7290A), which are shown in Fig.3. Fig.3 (a)−(d) are recorded when the coupling ratios of two fiber couplers (i.e. C_1 and C_2) utilized to construct the ring coupled cavity are the same, and their coupling ratios are 10/90, 20/80, 30/70 and 50/50, respectively. The relatively low fringe visibility (less than 0.4) is chiefly owing to no polarization controlling measures are taken in the array, and the large number of lobes is due to the poor filling factor (nearly 0.1) in the near field. According to the experimental investigating results, when the proportion of energy coupled into the ring cavity (relying on coupling ratio) is not less than 20%, obvious and stable interference patterns can always be obtained and the fringe visibility become larger with the increase of coupling ratio. When the proportion of energy coupled into the ring cavity is 10%, the two−wave interference patterns is also observed, but its fringe visibility is quite low and become unstable. Because the fringe visibility and stability of the interference pattern indicate the degree of phase locking between fiber lasers, it is mainly determined by the coupling strength between them. Therefore, we believe that efficient phase locking can be achieved only when the proportion of coupling energy is not less than 20%, and keeping the coupling strength strong enough is a necessary condition to obtain efficient phase locking.

Figure 4 (a) and (b) are the output power and combining efficiencies evolutions of the phased array at different pump power, when the coupling ratios of C_1 and C_2 are 10/90, 20/80, 30/70 and 50/50, respectively. When the pump power of two component lasers are 94.4 mW, the output power of the phased array are 46.9 mW, 46.4 mW, 45.6 mW and 43.7 mW with the corresponding coupling ratios mentioned above. Considering the output power of two component lasers when they operate independently with the same pumping condition are 24.6 mW and 25.5 mW, the calculated combining

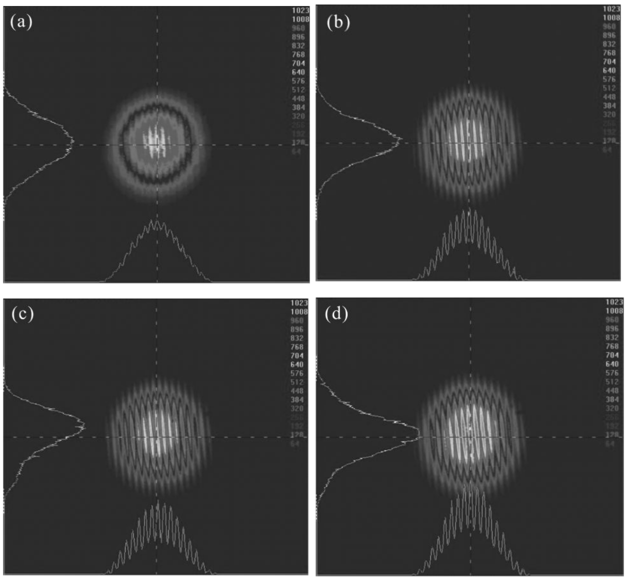

Fig.3 Far field interference pattern obtained with the same coupling ratios of C_1 and C_2

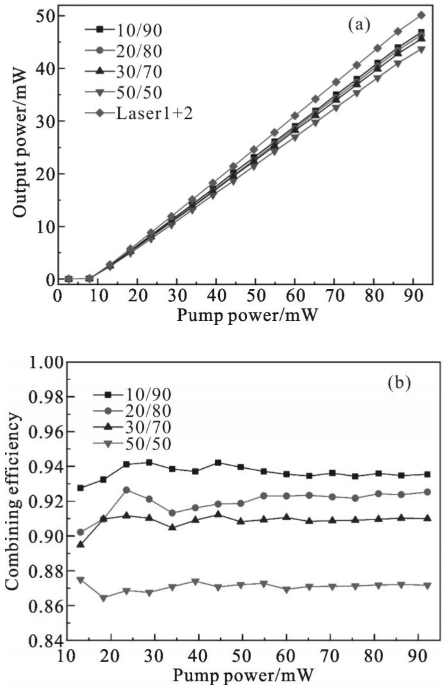

Fig.4 Output power and combining efficiencies evolutions of the phased array at different pump power

efficiencies with different coupling ratios are 93.6% , 92.6% , 91.0% and 87.2% . Moreover, when the component laser′s pump power is larger than 34 mW and it operates stably, the combining efficiency keeps nearly unaltered with the increase of pump power. Based on the above-mentioned experimental results, we find that the output power and combining efficiency of the phased array decrease regularly with the increase of coupling ratio, but the decrease amount is small. When the coupling ratio is not more than 30%, the combining efficiency is not less than 91%.

For the purpose of comparison, the curves of combining efficiency η and coupling coefficient κ as the functions of coupling ratio k are also obtained from Eq.(5), which are plotted in Fig.5 when the fiber couplers′ insertion loss γ_0 =0.02 and the power transmission coefficient T_0=0.98, 0.95, 0.90, 0.85. In our experiment, the parameters γ_0 =0.02, T_0 = 0.95, the calculated combining efficiencies are 93.8% , 92.7% , 92.2% and 91.7% when the coupling ratio k is 0.1, 0.2, 0.3 and 0.5, respectively. The theoretical analysis results are basically consistent with the experiments′, except they are slightly larger, especially when the coupling ratio is larger than 0.3. The main reason leading to the difference is owing to the actual cavity loss increased a lot in experiment with the increase of coupling ratio. Based on the power transmission property analyzed by intensity addition

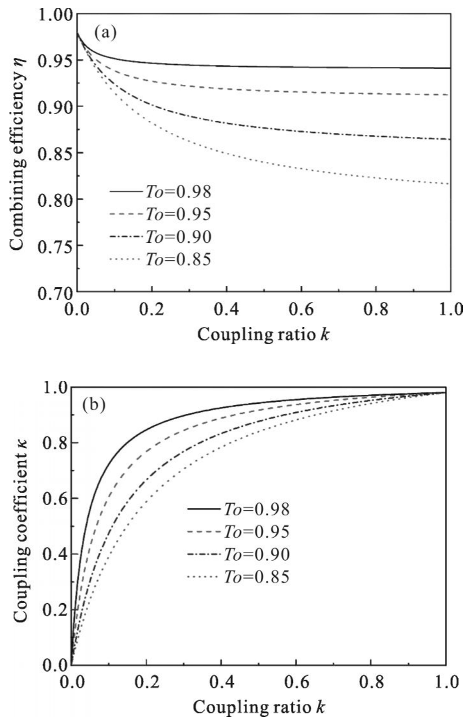

Fig.5 Calculated combining efficiencies and coupling coefficients as the functions of coupling ratio k when T_o= 0.98, 0.95, 0.90, 0.85, γ_0= 0.02

method, we have found that the combining efficiency decrease monotonously with the increase of coupling ratio k, whereas the coupling coefficient increases and coupling strength is enhanced. Therefore, we believe that increasing the coupling ratio can increase the coupling strength and decrease the efficiency, and decreasing the loss of the fiber ring cavity can improve both the coupling strength and the efficiency.

3.2 Phase locking with unsymmetrical coupling

When the coupling ratios of two fiber couplers utilized to construct the ring coupled cavity are different, the fiber couplers form a ring cavity with unsymmetrical coupling, and the far field interference patterns and output power are investigated and shown in Fig.6 and Fig.7. Figure 6 (a)-(c) are the far filed interference patterns recorded when the coupling ratio of C_1 is fixed to 20/80 and the coupling ratio of C_2 are 20/80, 30/70 and 50/50, respectively. Although there exist obvious coupling ratio difference between C_1 and C_2, clear and stable interference patterns are also obtained, and the fringe visibility and stability are slightly improved with the increase of coupling ratio difference, as long as the coupling strength between two fiber lasers is strong enough.

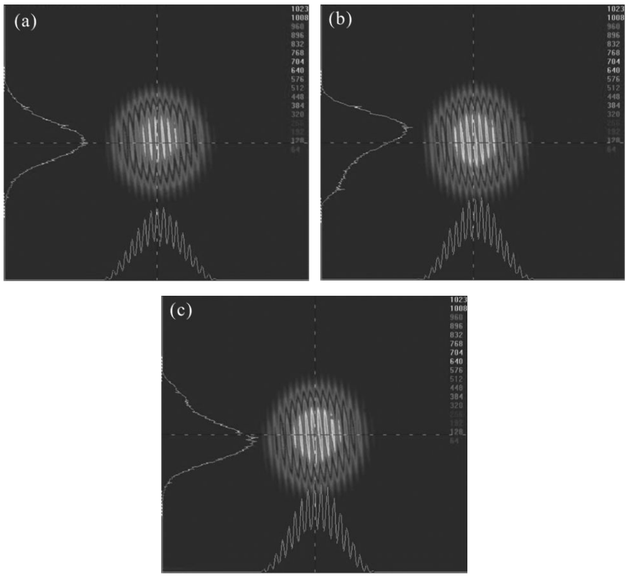

Fig.6 Far field interference pattern obtained with unsymmetrical coupling ratios

Figure 7 (a) and (b) are the output power and combining efficiencies evolutions of the phased array at different pump power, when the coupling ratio of C_1 is 20/80 and the coupling ratios of C_2 are 20/80, 30/70 and 50/50, respectively. When the pump power of two component lasers are 94.4 mW, the output power of the phased array are 46.4 mW, 46.0 mW and 45.3 mW with the corresponding coupling ratios mentioned above. Considering the output power of two component lasers when they operate independently with the same pumping condition are 24.6 mW and 25.5 mW, the calculated combining efficiencies with different coupling ratios are 92.6%, 91.8% and 90.4%. Moreover, when the component lasers' pump power is not less than 34 mW and they operate stably, the combining efficiency keeps nearly unaltered with the increase of pump power. Based on the above-mentioned experimental results, we have found that the output power and combining efficiency of the phased array decrease regularly with the increase of coupling ratio difference, but the decrease amount is not remarkable.

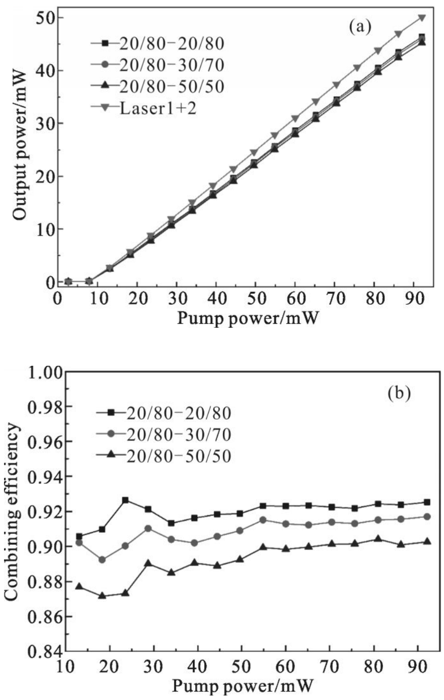

Fig.7 Output power and combining efficiencies evolutions of the phased array at different pump power

For the purpose of comparison, the curves of combining efficiency η and coupling coefficient κ as the functions of coupling ratio k with different coupling ratios are also obtained from Eq.(6), which are plotted in Fig.8 when the fiber couplers′ insertion loss γ_0=0.02 and the power transmission coefficient T_0 =0.95. In our experiment, the coupling ratio k_2 is 0.2, and the calculated combining efficiencies are 92.7%, 92.4% and 92.0% when the coupling ratio k_1 is 0.2, 0.3 and 0.5, respectively. The theoretical analysis results are slightly larger than the experiments′, especially when the coupling ratio is larger than 0.3. The main reason leading to the difference can be attribute to the real cavity loss increased a lot in experiment with the increase of coupling ratio. According to the theoretical analyzing results based on intensity addition method, we can find that when the coupling ratio k_2 is a constant, the combining efficiencies and coupling coefficients change monotonously with the varying of coupling ratio k_1, and increasing the coupling ratio can increase the coupling strength and decrease the efficiency.

According to the experimental and theoretical results obtained above, we believe that efficient phase locking can always be realized whether the coupling ratios of fiber

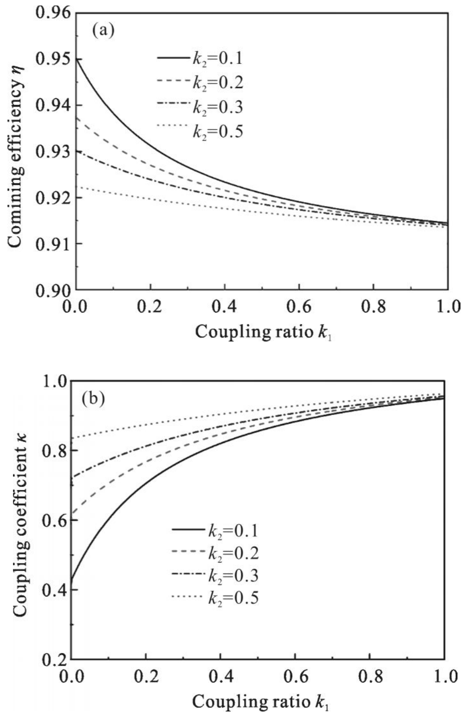

Fig.8 Calculated combining efficiencies and coupling coefficients as the functions of coupling ratio k_1 when T_o=0.95, γ_0=0.02

couplers utilized to construct the ring coupled cavity are equal or not. The difference in coupling ratios has little effect on the combining efficiency and interference pattern compared with the case of using equal coupling ratios, and the small coupling ratio difference is helpful for improving the stability of phase locking states due to the coupling structure′s symmetry is destroyed[20]. However, if the coupling ratios of fiber couplers are different remarkably in quantity, it is also not proper to use them to construct the common ring coupled cavity. Since the output power extracting from different ports will be different evidently, and it is harmful to coherent beam combining in the far field.

4 Conclusions

Proper optical coupling is a crucial factor to obtain efficient passive phase locking, and the phase locking performance is mainly determined by coupling strength among component lasers. Aiming at the passive phase locking configuration with a common ring cavity, the effect of coupling strength on the phased lasers′ coherence and combining efficiency has been investigated in this paper. The coupling model corresponding to the configuration is obtained and the intensity addition method is adopted to analyze the ring coupled cavity′s power transmission property, and the effect of magnitude and difference of fiber couplers′ coupling ratios on the circulating intensity in the common ring cavity and the output intensity of the phase locking array are investigated in theory. To validate the detailed effects, passive phase locking of two fiber lasers with a common ring coupled cavity has been demonstrated, and the effect of coupling strength has been studied by altering the fiber couplers′ coupling ratio. Both the theoretical analysis and experimental results indicate that it is quite necessary to bring adequate coupling strength to achieve effective phase locking, and improving the coupling strength by increasing the coupling ratio can ameliorate the coherence of the phase locking array and decrease the combining efficiency slightly, and small coupling ratio difference among component fiber lasers has very little effect on the phase locking performance.

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