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Coherent combining of fiber lasers using a ring coupled cavity and single-mode fiber filtering

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Abstract Coherent combining of two fiber lasers has been experimentally demonstrated by using a ring coupled cavity and single-mode fiber filtering technique. Their phases are primarily synchronized due to mutual injection coupling introduced by a common ring coupled cavity, and efficient phase locking is realized by utilizing a single-mode feedback fiber to filter the far-field pattern. The detailed experimental investigations indicate that the stability of phase locking can be improved significantly by this spatial filtering technique, and the far-field intensity distribution can be manipulated by controlling the position of the filtering fiber.

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1 Introduction

The high average power and high brightness laser source has wide-ranging applications in many fields, and continuous efforts are being made by lots of researching groups to obtain such a laser source. Since fiber lasers offer the advantages of compactness, high efficiency, good beam quality, convenient heat dissipation and flexible fiber delivery, they are quite suitable to construct a high average power and high brightness laser source by utilizing coherent beam combining techniques [1–4]. Generally speaking, coherent combining techniques can be categorized into two broad classes [2, 3]: side-by-side combining (tiled-aperture) methods and collinear summation (filled-aperture) methods. For the first class [5–16], multiple fiber lasers or amplifiers often realize phase locking through active controlling techniques or some kind of optical coupling, and the phased output beams are spatially separated in the near field and are coherently added in the far field. For the second class [17–23], the component laser beams are generally combined at the common parts of their compound cavity, thus power combining can be obtained in both near and far field. Since the collinear combined laser beam usually extracts from a single port, the ultimate power is still limited by the damage threshold of the common port, whereas this problem can be avoided naturally in side-by-side combining schemes due to their multiple output ports. However, the side-by-side combining schemes usually need to obtain tight optical coupling and have to keep their phase relation fixed at the output aperture, and it is really a difficult challenge to achieve this purpose. Fortunately, various schemes have been put forward to solve the problem, and notable achievements have been made in experiments [5–15].

To the best of our knowledge, almost all side-by-side combining schemes have employed special phase controlling measures to realize efficient phase locking, and typical schemes and main achievements are summarized in Table 1. For active phase controlling methods, they involve complicated phase detection and correction for each element of a fiber laser array [5–7]. For various passive self-adjusting schemes, they often require specially designed spatial filtering means to select the desired supermodes (array modes) [8–15]. In other words, the side-by-side combining techniques, which have the potential to obtain a laser source with higher output power and brightness thanks to their multiple separate gain media and emitting ports, have to introduce some kind of filtering or feedback measures to form a closed phase adjusting loop to keep all emitters output in-phase. As a consequence, most of the output energy

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Table 1 Typical phase locking schemes of fiber lasers and their special designed phase controlling measures

Name of the scheme		Max. output power and elements of the array	Combined effects	Phase controlling measures	References
Active phase controlling		470 W, 48 elements	phase error $<\lambda/30$	Active phase detection and correction	[5–7]
Self-organization or Self-adjusting	Self-imaging resonator	113 W, 4 elements	$V = 0.59$	Spatial filtering with metal wires at output mirror	[8–10]
	Self-Fourier cavity	6 W, 7 elements	$V = 0.84$	Spatial filtering with output ends of fiber lasers	[11]
	Talbot resonator	11 W, 37 cores of MCF	Gaussian-like pattern; In-phase mode operation	Talbot effect or spatial filtering with structured mirror	[12–14]
	Self-injection locking	0.24 W, 4 elements	$V = 0.94$	SMF filtering	[15]

Abbreviations appeared in table: V, fringe visibility; MCF, multicore fiber; SMF, single-mode fiber

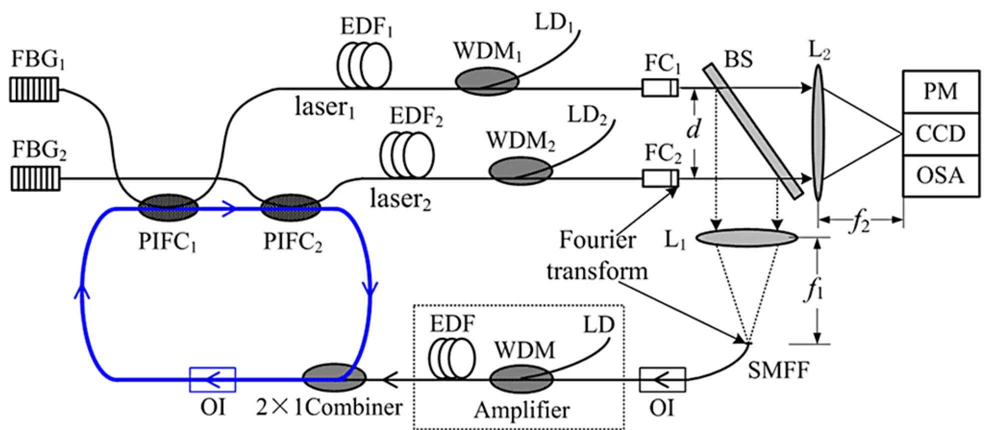

Fig. 1 Experimental setup of two fiber lasers phase locking array with a ring coupled cavity and single-mode fiber filtering. PIFC, polarization insensitive fiber coupler; WDM, wavelength division multiplexer; LD, 980 nm laser diode; FC, fiber collimator; BS, beam splitter with 4% reflection; L_1, L_2, two positive lenses with focal length $f_1 = 10$ cm, $f_2 = 40$ cm; d, the spacing of two output parallel beams

can be concentrated into the central main lobe in the far field (if the filling factor is close to 1).

In this letter, a novel phase locking scheme of fiber lasers based on a common ring coupled cavity and single-mode fiber filtering technique is proposed and demonstrated. Thanks to the special designed ring coupled cavity, the necessary optical coupling, which is always needed in passive phase locking techniques, is introduced among component fiber lasers, and mutual coherence and phase synchronization are partially obtained. However, the phase locking state is not very stable due to lacking necessary spatial mode selection measures and multiple supermodes operating simultaneously [16], thus a single-mode feedback fiber (SMFF) is introduced to collect the energy of wanted modes [15, 24] and feed them back into the ring coupled cavity, this is the so-called SMFF spatial modes filtering. The properties of this filtering technique are investigated in detail, and the phase locking stability of the array with and without using this filtering technique is particularly analyzed and compared by a laser beam analyzer.

2 Experimental setup and principle

The experimental setup for the proposed phase locking scheme is schematically presented in Fig. 1. Two individual fiber lasers all employ 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 1550 nm. The gain fibers are single-mode EDFs (Fibercore, DF1500F-980), and their lengths are 11.5 m and 10 m, respectively. Two 2×2 polarization insensitive fiber couplers (PIFC), with the coupling ratio of 80:20, 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 the 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 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 realize efficient spatial filtering, the mode-field diameter (MFD) of SMFF needs to be smaller than the central lobe size of in-phase mode. In our configuration, the spacing between two output beams is nearly 5 mm and the focal length of L_1 is 10 cm, thus we can calculate the lobe size of spatial mode as $\varphi = \lambda f_1/d \approx 31$ μm, which is obviously larger than the MFD of SMFF (nearly 10.4 μm) and the filtering condition is satisfied. Since the interference lobes are strip-shaped and their sizes are larger than the MFD of SMFF, a part of in-phase mode's energy will be coupled into the cladding or lost in free space. Considering that the reflected feedback power is low (usually on the milliwatts level), the risk of damage to SMFF is also low. To obtain enough feedback injection energy, a self-made erbium-doped fiber amplifier (EDFA) is inserted into the feedback loop to amplify the collected power. When the amplified feedback power reached nearly 4.7 mw, stable phase locking states were obtained in our experiment.

Two crucial parts of this configuration are the common ring coupled cavity and SMFF filtering, which are responsible for the stable phase locking output. The ring coupled cavity forms a common channel for mutual injection coupling among different fiber lasers, and mutual coherence is achieved by injection locking. For individual lasers, the ring sub-cavity also acts as a filter for longitudinal mode selection and stabilization. The SMFF filtering is essentially the same as self-Fourier or self-imaging filtering techniques [8–11]; they all utilize a spatial filter to bring loss difference between in-phase mode and other unwanted supermodes. The beam emitting plane and SMFF filtering plane forms a Fourier transform pair through a biconvex lens, and the filter size φ has to meet the equation $\varphi \leq \lambda F/D$ so as to realize efficient filtering, where F is the focal length of the lens, and D is the out-diameter of the emitting beams.

The operating principle and process of the coherent array can be primarily explained by the mutual injection locking mechanism. Each component fiber laser not only owns the individual feedback from its own FBG, but also owns the coupled feedback from the other fiber laser's FBG after passing through the ring coupled cavity, as well as a part of mixed output power which is coupled into the SMFF. These feedback electric fields will interact at the overlapped areas due to their coherence. By choosing the proper size and position of the SMFF, only the in-phase mode of the array can be coupled into it. The in-phase mode guided by the SMFF and the circulating field in the ring coupled cavity will be added coherently at the 2×1 combiner, and the mode satisfying constructive interference conditions in the ring cavity will be chosen to oscillate and the added output will be maximized. The similar coherent combining interactions among these fields will also occur at each of the PIFCs.

3 Results and discussion

3.1 Spatial filtering properties

When the ring coupled cavity and SMFF are introduced into the two fiber lasers array, their phase locking states are achieved consequently. The far-field interference patterns are recorded by an infrared CCD (Electrophysics, 7290A), which are shown in Fig. 2. We believe that the relatively low fringe visibility (nearly 0.4) is due to there being no polarization controlling measures in the array, and the large number of lobes (about 14) is due to the poor filling factor in the near field. Figures 2a and 2b are the patterns of in-phase and anti-phase modes of this array, respectively, which are obtained alternately when the SMFF moves transversely in the back focal plane of L_1 along the centerline perpendicular to the fringe pattern. Actually, the interference pattern moves as a whole to follow the shift of SMFF until the shift-amount

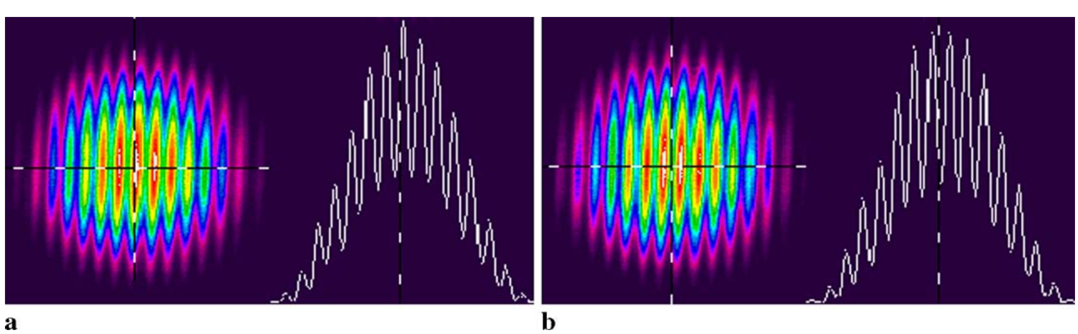

Fig. 2 Typical interference patterns and profiles of two phase locked laser beams. (**a**) In-phase mode, (**b**) anti-phase mode. The *dashed cross lines* appearing in figure are fixed reference signs, which are used to indicate the displacement of the fringe pattern

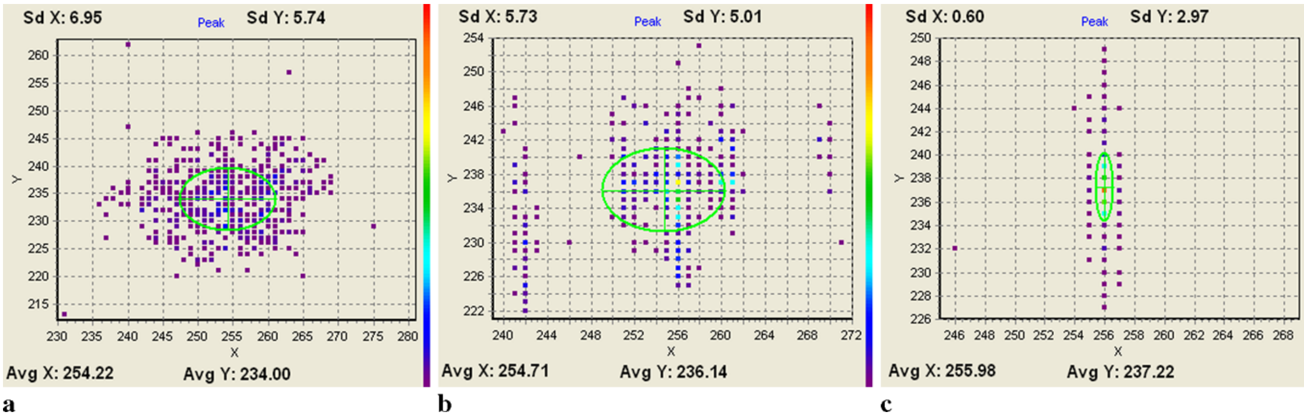

Fig. 3 Central peak location scatter plots with histogram color-coding of the fiber lasers array. (**a**) Free running state, (**b**) only with the ring coupled cavity, (**c**) with both the ring coupled cavity and SMFF filtering

is close to half a lobe size ($\approx \lambda f_1/2d$), and then the far-field intensity distribution of the in-phase mode changes into the anti-phase mode one or changes oppositely. This alternate process continuously emerged nearly ± 4 periods (4 to left, 4 to right) in experiment, i.e. when the transverse shift-amount of SMFF was within $\pm 4\lambda f_1/d$, the obvious fringe pattern could always be observed. However, if the shift-amount was beyond this range, the interference pattern became unstable: it moved slowly in transverse position and the fringe visibility changed continuously. Furthermore, the SMFF was also moved longitudinally along the centerline of the fringe pattern, and no significant change of intensity distribution was observed unless it was shifted out of the main pattern.

As a matter of fact, the SMFF is employed to stabilize the phase relationship of the component lasers of an array. If its position shift can alter the phase (optical path) differences from different emitters to the SMFF, another new supermode will emerge to compensate the change, and thus the far-field intensity distribution of the array will alter to follow the shift of SMFF. In other words, the far-field intensity distribution of the phase locking array can be handled by controlling the position of the filtering fiber.

3.2 Stability analysis

The output beam stability of the phase locking array is investigated based on the laser beam analyzer (LBA-PC, software version 4.22, Spiricon Inc.), and its beam stability program can collect centroid and peak data from LBA-PC and display them graphically. For the purpose of simplicity and clarity, about 500 sequential samples captured from LBA-PC are collected and analyzed together at a time, which costs nearly 87 seconds to realize this action. Considering that the peak value location of the output beam is the most important factor for judging its stability, special attention has been paid to it, and three peak location scatter plots with histogram color-coding including 500 samples are obtained and shown in Fig. 3. The units of these scatter plots are pixels, and the color of these points means the times they appeared at the given analyzing time (referring to the right-side histogram with color-coding). The standard variances (Sd X, Sd Y) and average locations (Avg X, Avg Y) of these 500 sequential samples are calculated as well; these are shown at the top and bottom of Fig. 3, respectively.

According to the statistical results of three output states of the array, we can clearly find the improvement of their output beam stability. When the two component fiber lasers operate at free running states, i.e. without any interaction or coupling existing between them and they just combine incoherently, the peak locations distribute randomly and irregularly in a relatively large area owing to unavoidable thermal and mechanical effects, which is shown in Fig. 3a. After the ring coupled cavity is introduced between the two lasers, we have noticed that 2 lobes of in-phase mode and 4 lobes of anti-phase mode appeared in Fig. 3b, and the spacing between two adjacent lobes is nearly 10 pixels. These discernable fringes indicate that at least partial coherence is achieved between them, although all their eigen-modes extract simultaneously and the output beam is not very stable. When both the ring coupled cavity and SMFF filtering are employed, the stability of the output beam is evidently improved, especially the fluctuation in the X-direction is well restrained, and the calculated standard variances of 500 samples decrease to 0.60 and 2.97 pixels in the X- and Y-directions, respectively. Only the in-phase mode is observed in Fig. 3c and almost all the peak values concentrate in the central lobe. However, the fluctuation of the peak location in the Y-direction cannot be controlled very well by the SMFF filtering technique, since the stochastic and fast move in the Y-direction just leads to the decrease of feedback power collected by SMFF and does not change their phase relationship. This issue can be expected to be solved when multiple emitters of an array are arranged in a central symmetry configuration, and the SMFF is set at the center axis of their

Fourier transform plane to collect the energy of in-phase array mode.

3.3 Output properties

The output power and spectrum properties of the component lasers and the phase locked array are investigated by the PM (ILX Lightwave, FPM8210H) and OSA (Agilent, 86142A). The component lasers (i.e. $laser_1$ and $laser_2$) share one 980 nm pumping LD by a 50:50 fiber coupler, and their output properties are measured when both the ring coupled cavity and SMFF are removed from the array. When the pump power reaches 176 mw, the output power of $laser_1$, $laser_2$ and the phase locked array are 27.8 mw, 28.0 mw and 48.7 mw, respectively. The combined efficiency, defined as the output power ratio of the array to the sum of $laser_1$ and $laser_2$, is 87% under this pump level. The output power stability of the phase locked array is also studied, and the maximum fluctuation is ± 0.03 dB over half an hour. Moreover, the measured operating wavelengths of $laser_1$, $laser_2$ and the phase locked array are 1550.040 nm, 1550.070 nm and 1550.055 nm, respectively, which means that the array has chosen their common longitudinal modes to oscillate even if the component lasers oscillate at different lasing wavelengths originally. In fact, two individual linear cavities, together with the ring coupled cavity, form a compound cavity with multiple gain media and output ports, and only the modes satisfying both the resonance phase and amplitude conditions in all sub-cavities have the lowest loss, and then they will be selected as the common modes to oscillate.

4 Conclusion

We have demonstrated efficient phase locking of two fiber lasers by using a ring coupled cavity and single-mode fiber filtering technique, and the spatial filtering properties of SMFF and the stability of output beam are particularly investigated. The research results indicate that the dominating in-phase supermode can be handled by controlling the single-mode filtering fiber's position with respect to the array's center axis, and the beam stability of the phase locked array can be significantly improved by employing this spatial filtering technique. Since the presented scheme is a typical side-by-side combining technique, compared with the tree or similar structures with only one output port [17–23], its thermal management and expandability become much more convenient. Moreover, the output linewidth of the coherent laser array is obviously narrower than the phase locked fiber amplifier array presented in [15] due to the compound cavity's mode selecting effect, whereas its configuration becomes relatively complicated. The array can be easily scaled up to more elements by adding more component lasers with different cavity lengths to the common ring coupled cavity, and the method offers the possibility of obtaining a high output power and a high brightness laser source.

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