Mutual injection phase-locking fiber laser with an extra-cavity based on a corner-cube

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ABSTRACT

Phase locking and coherent beam combination of two individual double-clad fiber lasers by a novel extra-cavity mutual injection-locking method based on a corner-cube are proposed and experimentally demonstrated. Steady interference stripes with high contrast ratio(about 81.7%) are observed. The output power of the phase-locked array exceeded 10W and the power combining efficiency is about 80%. No power-restriction optical components are utilized in our phase-locking experiment and the output power can be further up-scaled.

Keywords: fiber laser, coherent combining, mutual injection phase-locking , corner-cube

1. INTRODUCTION

As we all know, a single fiber laser with output power of 3000W has been reached [1], but the output power based on the existing technology is limited to further improve, because of the impact of multifarious factors such as thermal effects, nonlinear effects and so on. In order to achieve 100KW output power, coherent combining technology of multi-beam laser is an effective way, the core of which is to control the phase, so that each phase of the fiber laser output to maintain consistent. Multi-beam interference between each other (the same frequency, phase difference and polarization state) realize coherent superposition in order to obtain high power and brightness.

Coherent combining technology is divided into active and passive phase-locking. The latter is also called "self-organization /mutual-injection phase-locking", which means that a number of independent lasers by mutual injection may form a self-adaptive systems. When the system is stable, wavelengths and phases of the various lasers are reached the same state, we can get higher power combining efficiency, higher contrast ratio and so on. So it is the new trend and the most promising new way on development of coherent combining[2-4].

Taking an overview of the current reports in the field, including coherent program and the corresponding experimental results, they have their own limitations and difficulties, their experiments have not got the desired power output. The correlative study is still in the verification of principle and experience exploratory stage, a common flaw is low contrast ratio, low coherent combining efficiency and limited power upscale ability.

In this paper, a new "extra-cavity" mutual-injection phase-locking structure based on a corner-cube, is designed, and the experimental system is built. Mutual injection phase-locking of two individual double fiber lasers is experimentally demonstrated. Steady interference stripes with high contrast ratio （about 81.7%）are observed, more than 10W output power is achieved , and the average power combining efficiency is up to 80%. The project has a strong capacity to enhance and enlarge power upscale function., is expected to achieve more coherent combining on optical fiber lasers and obtain the target laser output of high brightness, high power, high-energy concentration. It is very suitable for energy applications and a promising new technologies.

2. THE BASIC PRINCIPLES

Mutual injection phase-locking method is not a new concept, if multi-individual fiber lasers' signal frequency is close to a certain extent, the oscillation mode of fiber lasers is interrelated and mutual influencing, in order to achieve the same multi-frequency phase-locking laser output.

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International Symposium on Photoelectronic Detection and Imaging 2009: Laser Sensing and Imaging,
edited by Farzin Amzajerdian, Chun-qing Gao, Tian-yu Xie, Proc. of SPIE Vol. 7382, 73820U

Here, taking coherent combination of two fiber lasers theoretical research for example, the two laser light intensity and optical gain of the slowly varying equation as follows [5-7]:

$$\frac{dE_1}{dt} = \tau_c^{-1}\left[(G_1 - \alpha_1)E_1 - kE_2\right] + i\omega_1 E_1 \quad (1)$$

$$\frac{dG_1}{dt} = \tau_f^{-1}\left(p_1 - G_1 - G_1\left|E_1\right|^2\right) \quad (2)$$

$$\frac{dE_2}{dt} = \tau_c^{-1}\left[(G_2 - \alpha_2)E_2 - kE_1\right] + i\omega_2 E_2 \quad (3)$$

$$\frac{dG_2}{dt} = \tau_f^{-1}\left(p_2 - G_2 - G_2\left|E_2\right|^2\right) \quad (4)$$

$$E_1 = A_1 \exp(i\phi_1) \quad (5)$$

$$E_2 = A_2 \exp(i\phi_2) \quad (6)$$

Where, E for the electronic field of fiber laser, and G for the optical gain coefficient, α for the cavity loss coefficient, k for two laser energy mutual injection coefficient, p for pumping coefficient, τ_c for the photons time in the resonant cavity, τ_f for fluorescence lifetime, ω for the laser operating frequency, ϕ for the laser initial phase, A is the amplitude for the light intensity, subscript 1 and 2 apply to the two different lasers.

In the experiment, because of almost the same parameters of pump source, laser medium in two used laser, for the sake of simplification, we consider that the two pump lasers coefficient, gain coefficient, attenuation coefficient and light intensity are the same, then (1) - (6) can be concluded as follows:

$$\frac{d\Delta\phi}{dt} = 2k\tau_c^{-1}\sin\Delta\phi + \Delta\omega \quad (7)$$

Where, $\Delta\phi = \phi_1 - \phi_2$, $\Delta\omega = \omega_1 - \omega_2$ for the phase difference and the frequency difference between the two lasers. From (7), we can see that only when $\Delta\omega$ meet $\left|\Delta\omega\right| \le 2k\tau_c^{-1}$, the phases of two lasers can change over time converges to a fixed value, so that $\frac{d\Delta\phi}{dt} = 0$,which is the realization of two phase locking lasers. Here, the term $2k\tau_c^{-1}$ is called " mutual injection phase-locking bandwidth".

Therefore, in the experiment, we must strictly control the two laser frequency difference, so that meet the scope of the mutual injection phase-locking bandwidth. Figure 1-a is shows the difference between single injection phase-locking bandwidth and mutual injection phase-locking bandwidth; we can see that mutual injection phase-locking bandwidth area is about 2 times than single injection phase-locking bandwidth area in the experiment. It is easier to achieve two independent lasers into the mutual injection phase-locking. Figure 1-b shows the relationship between mutual injection phase-locking bandwidth and mutual injection energy. We can see that higher mutual injection energy(k), more wider phase-locking bandwidth make more easier to achieve phase-locking.

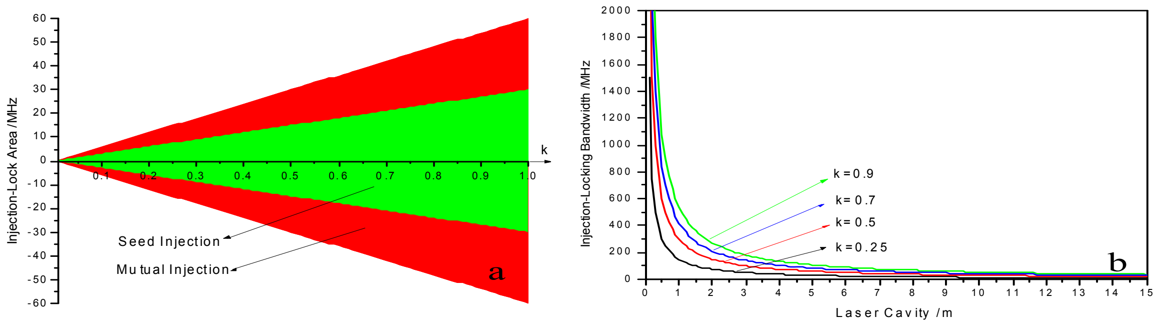

Figure 1. Comparison between single injection phase-locking and mutual injection phase-locking bandwidth(a), the rate relationship between mutual injection phase-locking bandwidth and mutual injection energy (b)

3. SCHEME DESIGN AND EXPERIMENT

3.1 Scheme design

Fig.2 shows the configuration used for beam combining of two individual fiber lasers by mutual injection-locking. Two fiber-coupled continuous wave diode lasers with emitting wavelength of 975nm were used as pump sources in our phase locking experiment. In the laser array, the two fiber laser cavities were consisted of two fiber Bragg grating (FBG, R>99%) and a flat mirror M1 with reflectivity of 85% for 1030~1100nm, and M1 is used as the output mirror of the phase-locked fiber laser array. Two 15m long Yb^{3+}-doped double-clad star-shaped fibers (YDDCF) with 7μm core diameter and 0.4 numerical aperture are used as the active media. In the resonators, laser beams emitted from the two fiber lasers are collimated by two fiber collimators (FC) which are placed closely to each other and their center to center space is 10mm. As shown in Fig.2, the mutual inject-locking is realized by a beam splitter and a corner cube. In the process, the output of fiber laser 1(FL1) is split into two beams (transmitted beam and reflected beam) by the polarizer. The transmitted beam passes through the splitter and then is reflected into the exact reverse direction by a corner cube. The reflected beam from the corner cube faces the beam splitter again, half of the beam passing through the splitter and finally being injected into fiber laser 2(FL2). And vice versa, the two fiber lasers, which are in symmetrical place, inject laser energy into each other. A high reflecting mirror M2 (R>99.5%) for 1030~1100nm is introduced to increase the mutual injecting lights and enhance the output power. Because of three reflectors and the role of edge in a corner-cube, three laser beams will be split into six separate symmetric laser beams in space, of which conjugate beams in space and time were completely coherent: 1 and 4, 2 and 5, 3 and 6,but unsymmetrical place is partially coherent(as shown in Figure 3).

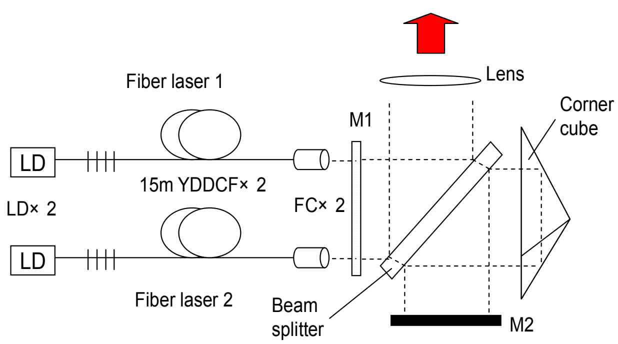

Figure 2 Mutual injection phase-locking fiber laser experimental system with an extra-cavity based on a corner-cube

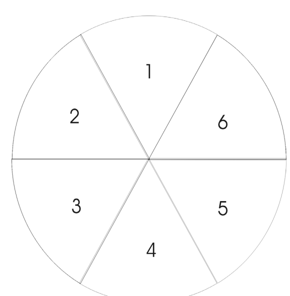

Figure 3 Three pairs of conjugate surface diagram in bottom of corner-cube

The question is how to make six lasers achieve phase-locked or coherent combination. We have devised a clever program, just as shown in Figure 4. Making full use of three cross-connected optical gain fibers, as a result of the conjugate effect, one of the character in a corner-cube, we achieve mutual injection phase-locking coherent output. One end of an fiber laser is connected to surface 1, and the other end is connected to surface 2. The same to other two fiber lasers, respectively, 3、4 and 5、6. It is easily understandable that surface 1 and surface 4 are phase conjugate, while surface 1 and surface 2 are connected with an optical fiber, so we achieve sides 1、2and 4 mutual injection, the same principle to other sides. Therefore by this skillful way, we can realize mutual injection of the sides from 1 to 6. By mutual injection phase-locking of the six fiber lasers, every output beam passed through the corner-cube has the same oscillation and dissemination process. So we achieve the coherent combining output containing the same phase、polarization state and frequency laser light.

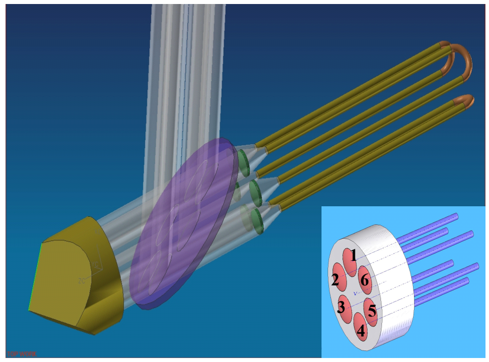

Figure 4 Program of mutual injection phase-locking fiber laser based on a corner-cube

3.2 Experiment and results

In order to verify the correctness of the program shown in Figure 2, we have adopted two-way mutual injection phase-locking fiber laser experimental device with an extra-cavity based on a corner-cube, launched the experiment on a far field intensity distribution and power combining efficiency.

3.2.1 The far field light intensity distribution changes before and after coherent combining

To characterize the beam profile, we place a lens with focal length of 1 m at a distance of 5cm away from the output mirror. In the experiment, adjust the optical path accurately, in order to achieve the highest mutual injection efficiency, also make M1 and two fiber laser synchronization. Here, using LBA-FW-SCOR20 laser beam analyzer produced by Spiricon company, we have measured the far field light intensity distribution changes before and after coherent combining of two-way fiber laser. We examine the beam profile in the far-field with an infrared charge coupled device (CCD) placed at the focus of the lens. When the two fiber lasers are turned on, we first measured the original far-field beam profile of FL1 and FL2 as shown in Fig.5(a) and Fig.5(b), and then measured the superposition of the two parallel free running beams when the mutual injection phase-locking system has not realized using a piece of metal block placed between the beam splitter and corner-cube in order to prevent the two-way mutual injection lasers.

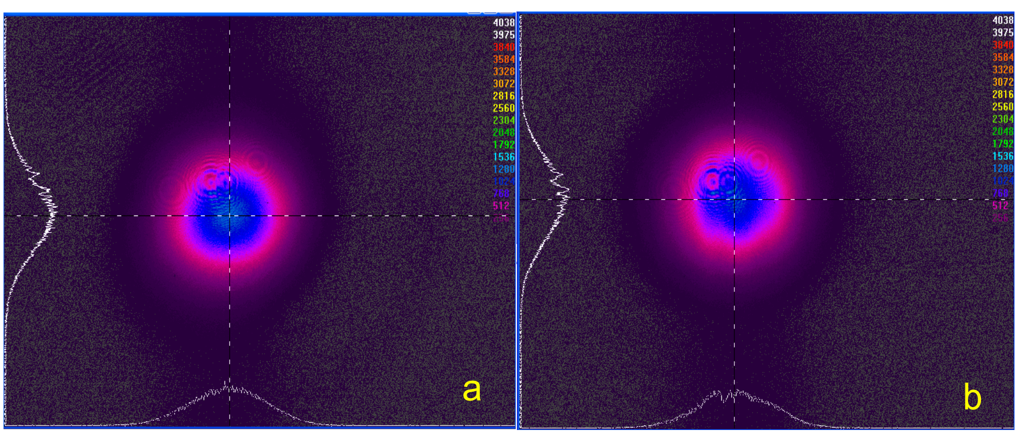

Fig.5 Far field pattern of the two free running fiber lasers (a) fiber laser1, (b) fiber laser2

The free running far field superposition pattern is shown in Fig.6(a), from which it can be seen that the field are simply incoherent superposition of two individual fiber lasers, with no coherent strips being observed. However, when the two lasers are in the phase locked state by adjusting the mutual injection phase-locking system well, coherent strips with high contrast ratio coming on the screen, as shown in Fig.6(b), which demonstrates that these two fiber lasers have been successfully injection-locked. The far-field intensity distribution appear very clear interference stripes. That is evident amplitude coherent combining state of two-way fiber laser. In accordance with the relevant calculation method on contrast ratio, it is about 81.7%. Observed in a long time, light intensity interference pattern of the two-way fiber laser does almost no jitter and has a very high stability, which illuminates that two-way fiber laser has got to phase-locking state and achieved the experimental system coherent combining. The contrast of the strips is very stable and does not show any decrease in a long time observation.

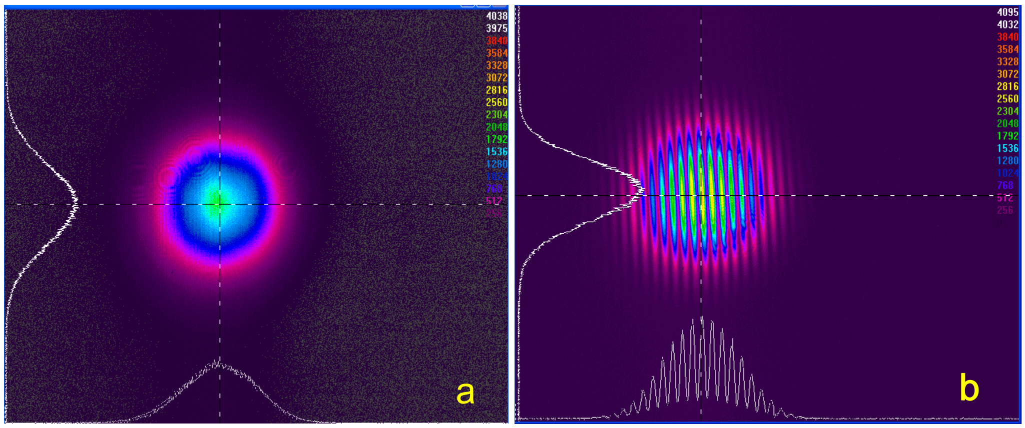

Fig.6 Far field pattern of the two fiber laser array in (a) free running, (b) mutual injection

3.2.2 The power combining efficiency

The power combining efficiency is another important coefficient of laser coherent combining. For two-way coherent combining laser, if the laser beam's power combining efficiency is below 50%, then the output power will be less than single-way laser', it will have no meaning. So the higher the power combining efficiency is, the better the result that we expect to achieve coherent combining method is. The power combining efficiency is defined as $\eta = P/(P_1 + P_2)$, where P is the coherent combined output power of the array, and P1 and P2 are the output power of the two free running fiber lasers.

The experiment follows these steps: Firstly, without the corner-cube, FBG and M1 as the fiber laser cavity, adjust the optical path Precisely in order to achieve the stability output of two-way fiber laser. When the output power is up to maximum, the laser can achieve the best resonant state. At this point, test change curve on the two-way fiber laser output power with different pump current. Under the highest pump level, two-way fiber laser (FL1 and FL2) maximum output power is 6.9W and 7.1W at the output mirror M1, respectively. That means, in the same current conditions, the output power summation of two-way fiber laser is 14W, as the denominator of the power combining efficiency. Secondly, when the system is in coherent combining state, in the same Pump current conditions, test change curve on the two-way fiber laser output power with different pump current, take the coherent fiber laser array output power as a molecule. In the experiment, the maximum output power of the coherent combining laser array is up to 10.6W. So we can get the power combining efficiency of 76%. The result on change curve of the two-way fiber laser and the independent fiber laser output power with different pump current, as well as the corresponding power combining efficiency, is shown in figure 7. From multiple sets of experimental data, we can obtain the average power combining efficiency is about 80%. No power-restriction optical components are utilized in our extra-cavity mutual injection structure, therefore the coherent output power can be further up-scaled.

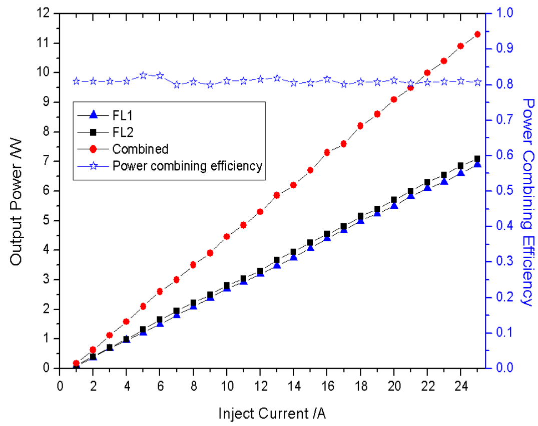

Figure 7 the change curve of the output power and the corresponding power combining efficiency before and after coherent combining of two-way fiber laser

4 CONCLUSION

In the paper, we utilized an external cavity based on a corner-cube to get mutual injection phase-locking,. A 10.6 W phase-locked laser array of two individual double-clad fiber lasers are experimentally demonstrated. Steady interference stripes with high contrast ratio(about 0.81) are observed, and the average coherent power combining efficiency of the two DCF lasers is about 80%. Our mutual injection-locking structure is simple and no active control of the phase, output power and fiber lengths of individual fiber lasers are needed. Therefore, it provide a new approach for phase locking of fiber lasers. That proves the correctness of the scheme proposed by mutual injection phase-locking fiber laser with an extra-cavity based on a corner-cube. The result of this experiment has very important value. At the same time, the experiment is very important to the follow-up study of fiber laser coherent combination, one can make full of the experimental platform to verify and revise the theoretical research results, and the other can establish principle experiment basis of coherent combining technology in fiber laser with an external cavity based on a corner-cube.

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