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Coherent combination of mutual injection phase-locked fiber lasers with a corner cube reflector

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ABSTRACT

We present a new method of the mutual injection phase-locked coherent combination of fiber lasers based on corner cube reflector (CCR). The theoretic calculation of phase difference and far-field intensity distribution of coherent beams obtained by the CCR has been carried out on this work. The relation between the far-field optical intensity distribution and the CCR rotation angles is analyzed in the case of mutual injection. The coherent combination experiments of mutual injection phase-locked with two and four fiber lasers are performed. The experimental results reveal that the far-field intensity distribution in the two free running fiber lasers is good agreement with the theoretical calculation. In the two internal mutual injection structures, the coherent combination output power goes up as high as 54 W, and power combined efficiency of more than 90% and fringe contrast about 90% are obtained. The far-field intensity distribution is the same as the typical coherent combination pattern of two-dimensional fiber laser arrays, the experimental results also show that the coherent combination output with more laser beams and higher power with a good beam quality could be realized by the current scheme.

1. Introduction

Beam coherently combining is of great interest due to the fact that the individual fiber laser is capable of delivering high output powers with a good beam quality.

In general, the phase-locked methods of the coherent beam combination technique in the fiber lasers include active phase-locked and passive phase-locked. In the active phase-locked mode, the phase of each laser beam must be controlled in real-time in order to make each laser operating at a constant phase difference. Although a high output power could be obtained in the active mode [1–3], the phase of each sub-laser must be detected and compensated. Therefore, the configuration of the laser is often excessively precise and complex [4]. In the passive phase-locked mode, the lasers are combined into self-adaptation system in some way (e.g. evanescent wave coupling, sharing end-face reflectors and nonlinear effect). When the adaptive system works steady, the wavelength and phase of each laser are locked automatically, and the stable output could be obtained. So far, many combination schemes with passive phase-locked mode have been introduced in various literatures, e.g. self-imaging resonator [5,6], self-adjusted phase-locking with coupler [7,8], and multi-core fiber coherent combination [9] etc. Moreover, more and more new experimental results are reported gradually [10–17]. Among numerous schemes, the mutual injection phase-locked mode is a more effective method in passive phase-locked model.

Based on early research of solid-state laser with corner cube resonator, the corner cube reflectors (CCR) is a natural component for mutual injection coherent combination [18,19]. Therefore, the CCR is also employed as the coherent beam combination element in fiber lasers in order to achieve the coherent combination output of the mutual injection phase-locked lasers. In this scheme, the mutual injection phase-locked with the CCR could be considered as a completely self-organized system of passive phase-locked model.

Firstly, the principle of the coherent beam combination achieved by the mutual injection phase-locked laser with the CCR is briefly described. Secondly, the intensity distribution at far-field of the coherent combination beam is calculated theoretically. Thirdly, the experiments of coherent beam combination with two and four fiber lasers have been carried out. Finally, the experimental results and the possibilities for extending this new scheme are discussed.

2. Principle and process of mutual injection phase-locked method with the CCR

Due to the characteristics of the retro-reflection and depolarization effect of CCR, the mutual injection phase-locked method with the CCR can be realized. The retro-reflection of the CCR could make the frequencies of the symmetric injection of the N independent lasers into the identical frequencies. Although the oscillation frequency and path of the N lasers are different before mutual

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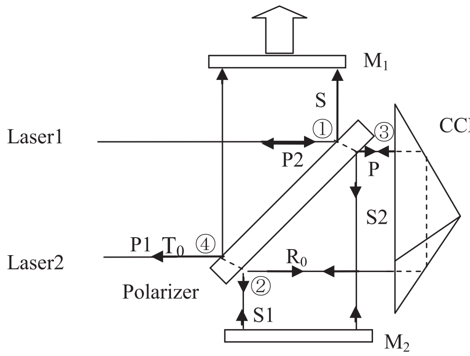

Fig. 1. The sketch of the energy mutual injection using the CCR in two fiber lasers.

injection, at once the beams passing the corner cube reflector (CCR), in which the N lasers would have similar oscillation and identical path for mutual injecting, therefore they could get coherent beams output with identical frequencies. The mutual injection energy of each laser would be controlled by depolarization effect and axial rotation of the CCR. Moreover, the phase difference and far-field intensity distribution of the output could be changed. Based on the two characteristics (retro-reflection and depolarization) of the CCR, the optimal mutual injection phase-locked output could be realized.

The process of the mutual injection with CCR is shown in Fig. 1. The beam from laser1 is divided into two linear polarized lights (singed as P-light and S-light) when it is incident on the polarizer ①. S-light will be reflected and becomes resonance beam through M1. P-light goes through the polarizer and the CCR. Due to depolarization effect of the CCR, P-light becomes elliptical polarized light. Then, the elliptical polarized light is divided into another P1-light and S1-light (taking T_0 as its transmission) at the polarizer ②. P1-light is incident upon laser2. S1-light is reflected out of the cavity, resulting the loss of the beam energy. In order to decrease the cavity loss and increase energy output, a mirror M_2 is used in our experiment to make S1-light reflected to the position ②. Then the S1-light becomes elliptical polarized light through the CCR. And the elliptical polarized light is also divided into P2-light and S2-light at the polarizer ③ again. P2-light is incident on laser1. The S2-light is reflected by the polarizer again and repeats the same cause of S1-light.Thus, the energy injected into laser 2 will be raised to a steady value after several repetitions. Likewise, the energy from laser 2 can inject into laser 1 with the same process. Finally, the mutual injection phase-locked of two fibers lasers have been performed by use of the CCR.

3. Numerical simulation of far-field intensity distribution of coherent beam combination with CCR

Because of the inherent characteristic of fiber laser, it is easy to realize single longitudinal mode and single transverse mode operation by using single mode fiber. The literature [21] supplies the equations for the fiber laser with energy mutual injection, which can be employed to describe the relation of light intensity, gain and the amount of mutual injection. The equations can be simplified into [22,23]

$$\frac{dA_1}{dt}=\frac{1}{\tau_c}[(G_1-\alpha)A_1-\kappa A_2\cos\Delta\varphi] \tag{1a}$$

$$\frac{dG_1}{dt}=\frac{1}{\tau_f}(p_1-G_1-G_1A_1^2) \tag{1b}$$

$$\frac{dA_2}{dt}=\frac{1}{\tau_c}[(G_2-\alpha)A_2-\kappa A_1\cos\Delta\varphi] \tag{1c}$$

$$\frac{dG_1}{dt}=\frac{1}{\tau_f}(p_2-G_2-G_2A_2^2) \tag{1d}$$

$$\frac{d\Delta\varphi}{dt}=\frac{\kappa}{\tau_c}\left(\frac{A_1}{A_2}+\frac{A_2}{A_1}\right)\sin\Delta\varphi+\Delta\omega \tag{1e}$$

where, A_1 and A_2 are the amplitudes of the two lasers respectively; G_1 and G_2 are the gain coefficients; α is the cavity attenuation coefficient; p_1 and p_2 are pumping coefficients; τ_c is the cavity round trip time; τ_f is the fluorescence time of the upper lasing level of the Yb^{3+} ion; $\Delta\varphi=\varphi_1-\varphi_2$ is the phase difference of two lasers; $\Delta\omega=\omega_1-\omega_2$ is the frequency detuning difference of the lasers; κ is the mutual injection coupling coefficient, related to T_0, the single transmission of polarizer at position ④ shown in Fig. 1

$$\kappa=\frac{T_0}{2[1-(1-T_0)^2]} \tag{2}$$

and

$$T_0=\frac{1}{1+|X|^2} \tag{3}$$

where, X is the depolarization magnitude of CCR. If CCR is made of K9 quartz (refractive index is 1.46), then [20]

$$X=\frac{-0.0929+i0.9824\sin 2\theta}{-0.1622-i0.9824\cos 2\theta} \tag{4}$$

where, θ is rotation angle of CCR. Here, the initial value of axial direction of the polarizer (namely the polarization azimuth angle of linear polarized light which passes the polarizer) is assumed as zero.

Based on the above differential Eqs. (1a)–(1d), the process of the whole system could be calculated, and the time dependent of variables such as the output intensity and phase difference can be analyzed, then the intensity distribution of coherent combination can be plotted.

According to formula (4), when the CCR was rotated θ degree clockwise, the depolarization magnitude X will be changed, which will change the T_0 and κ from the formulas (2) and (3). Thus the phase-locked difference $\Delta\varphi$ and laser output magnitude A or intensity I will be changed. Finally, the far-field intensity distribution of the beam combination with CCR must be changed.

Assuming wavelength λ is1064 nm, waist radius ω_0 is 1 mm, duty ratio γ is 0.35, and the frequency detuning difference of the lasers $\Delta\omega$ is 3×10^6 Hz. When rotation angle θ of the CCR is 0, 15°, 30°, 45°, 60°, 75°, 90° and 105°, the far-field intensity distributions is shown in Fig. 2.

Fig. 2 reveals that the profile of interference fringes is lower and lower when θ is less than 45°, and then it will be higher and higher from 45° to 90°. Meanwhile, the position of primary peak of interference fringes has a tiny left-shift with CCR rotation.

Generally, if $\Delta\omega$ is zero while initial phase difference is not equal to zero, the output mode of the two lasers is out-of-phase mode (namely $\Delta\varphi=\pi$). However, in practice, the frequency difference $\Delta\omega$ is not of zero, such as $\Delta\omega$ is about 3×10^6 Hz in current experiment. Therefore, the phase locking difference $\Delta\varphi$ in current experiment is not but close to π. And the nearer the $\Delta\varphi$ approximates to π, the closer the distance between the interference fringes and out-of-phase mode is.

4. Experimental results and discussions

In order to examine the effect of the coherent beam combination of the fiber lasers, the feasibility and practicality of higher