Theoretic analysis on mutual injection phase-locking fiber laser array

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Received December 9, 2010; accepted January 10, 2011; posted online June 29, 2011

We report on a new technique of mutual injection phase-locking fiber-laser array. This technique uses a 45° beam splitter as coupling device. Injection phase-locking process of the fiber-laser array is simulated and analyzed. Results show that constant values of phase differences are related to initial phases. Reflectivity of the beam splitter and transmissivity of cavity reflectors should be properly optimized in order to make injection phase-locking easier.

OCIS codes: 060.2320, 060.3510, 140.3325, 140.3510.
doi: 10.3788/COL201109.S10305.

High-power fiber lasers are becoming increasingly competitive in applications such as industrial processing, communication and directional power weapon because of their advantages, including compactness, reliability, heat emission efficiency, synthesis efficiency, and beam quality. Currently, the output power of the single fiber laser has already exceeded 10 kW[1]. However, due to nonlinear effects, thermal damages, and optical damages of fiber devices, the output power of the single fiber laser is limited[2]. To obtain high output power and high beam quality, coherent combining of lasers has been put forward as a promising technology. Coherent combining can be divided into two categories according to the different phase-locking method: active phase-locking coherent combining and passive phase-locking coherent combining[3−6]. Active phase-locking coherent combining is complex and expensive because it needs to detect and compensate for the beam phases. In contrast, passive phase-locking coherent combining has the advantages of reasonable structure and low price. Mutual injection phase-locking fiber-laser array belongs to passive phase-locking coherent combining. It has been regarded as a promising technology[7,8] because it is easy to implement and has high synthesis efficiency. Mutual injection phase-locking of the three fiber lasers has been achieved using an all-fiber coupling loop[8]. However, to date, available all-fiber couplers cannot bear high power and their output power is also limited.

In this letter, we report on a new technique of mutual injection phase-locking fiber-laser array which uses a 45 degree beam splitter as coupling device. Mutual injection phase-locking of four fiber lasers is simulated. Time evolutions of phase differences and amplitudes are analyzed. We find that the reflectivity of the beam splitter and the transmissivity of cavity reflectors should be properly optimized in order to make injection phase-locking easier.

The mutual injection phase-locking fiber-laser array is shown in Fig. 1, in which lasers 1−4 are four fiber lasers. C1–C8 are eight multimode pump combiners which can be spliced into several diode modules (LD) with multimode fibers. Fiber Bragg Grating (FBG) 1−4 are four Bragg gratings with transmissivity T. They are used as cavity reflectors of the four fiber lasers. FBG 5–6 are four other Bragg gratings. They are used as output couplers of the four fiber lasers. Endcaps (EC) 1−4 are four fiber endcaps to avoid optical damage. Outputs of the tail fiber from OC1–OC4 are collimated. They reach the 45 degree beam splitter, which reflects 50% and transmits 50% of each beam. The reflected beams and transmitted beams leak into other lasers. Thereby, the four lasers are mutually injected.

According to the above analysis, the time evolutions of the complex, slowly varying electric field E and gain G of lasers[9−11] are described by the following slowly varying equations:

$$\frac{\mathrm{d}E_j}{\mathrm{d}t} = \tau_c^{-1}[(G_j - a_j)E_j - \kappa_{j+}E_{j+} - \kappa_{j-}E_{j-}] + i\omega_j E_j, \quad (1)$$

$$\frac{\mathrm{d}G_j}{\mathrm{d}t} = \tau_f^{-1}(p_j - G_j - G_j\,|E_j|^2), \quad (2)$$

where ω_j is the angular frequency, p_j is the pump coefficient, α_j is the cavity loss coefficient, and τ_c is the cavity round trip time. The laser cavity is from the cavity reflector to the output coupler. Assume τ_c of the four fiber lasers are the same. τ_f is the fluorescence time of

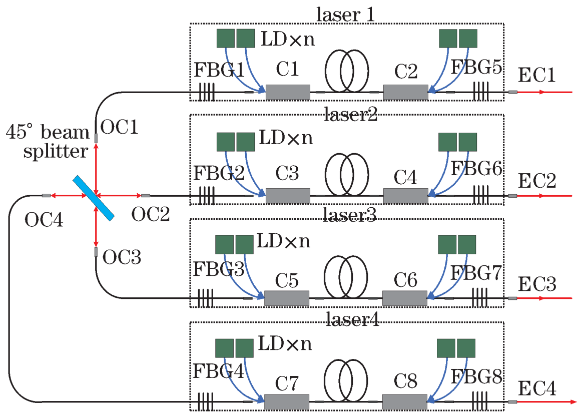

Fig. 1. Schematic diagram of the four-fiber-laser array.

Table 1. Parameters Used in the Simulation of Mutual Injection Phase-Locking of the Laser Array

Parameter	Symbol	Numerical Value
Amplitude of Laser j	$X_j(0)$	0.5
Gain of Laser j	$G_j(0)$	0.4
Pump Coefficient of Laser j	P_j	1.2
Cavity Loss Coefficient of Laser j	α_j	0.4
Cavity Round Trip Time	τ_c	0.2 μs
Fluorescence Time of the Upper Lasing Level	τ_f	0.2 ms
Angular Frequency of Laser j	ω_j	2^{15} Hz

the upper lasing level. $\kappa_{j+} = T\times R$ and $\kappa_{j-} = T\times(1-R)$ are the coupling coefficients, where T is the transmissivity of FBG, R is the reflectivity of the beam splitter, and j denotes laser j. Outputs of the tail fiber of laser j is reflected by 50% and transmitted by 50% at the beam splitter. The reflected beam leaks into laser $j+$ with coupling coefficient κ_{j+}. Furthermore, the transmitted beam leaks into laser $j-$ with coupling coefficient κ_{j-}.

In terms of amplitude X_j and phase ϕ_j, the electric field E_j can be written as $E_j = X_j\exp(\mathrm{i}\phi_j)$. Then, Eqs. (1) and (2) are reduced to

$$\frac{\mathrm{d}X_j}{\mathrm{d}t} = \tau_c^{-1}[(G_j - a_j)X_j - \kappa_{j+}X_{j+}\cos(\phi_{j+} - \phi_j) - \kappa_{j-}X_{j-}\cos(\phi_{j-} - \phi_j)], \quad (3)$$

$$\frac{\mathrm{d}\phi_j}{\mathrm{d}t} = \omega_j - \frac{\kappa_{j+}X_{j+}}{\tau_c X_j}\sin(\phi_{j+} - \phi_j) - \frac{\kappa_{j-}X_{j-}}{\tau_c X_j}\sin(\phi_{j-} - \phi_j), \quad (4)$$

$$\frac{dG_j}{\mathrm{d}t} = \tau_f^{-1}(p_j - G_j - G_jX_j^2). \quad (5)$$

Equations (3)−(5) describe the time evolutions of amplitudes, and phases and gains of each laser. The key to phase-locking is that the differences between the phases described by Eq. (4) achieve constant value. In the following analysis, laser phases are described by the differences between them. $\Delta\phi_{1j}=\phi_j-\phi_1$ (j=2, 3, 4) refers to the differences between the phases of lasers 2−4 and the phase of laser 1.

A four-fiber-laser array is a complex nonlinear system. Its phase-locking process can be simulated by calculating Eqs. (3)−(5) with a difference method. The time step is 50 ns. Under the condition that lasers were all the same, except at their initial phases, Fig. 2 shows the time evolutions of amplitudes and phase differences

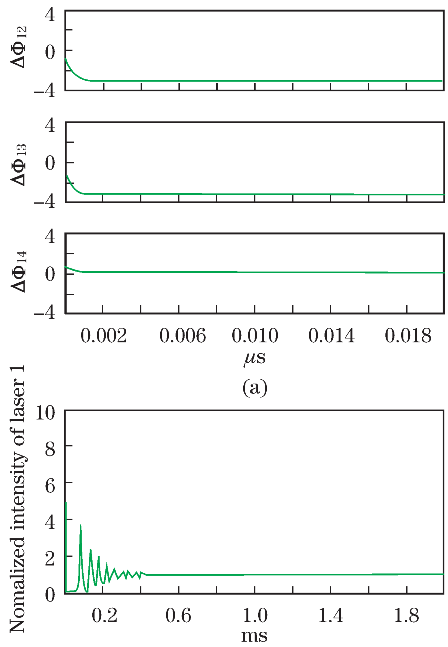

Fig. 2. Time evolutions of (a) phase differences ϕ_{1j} and (b) amplitude of laser 1.

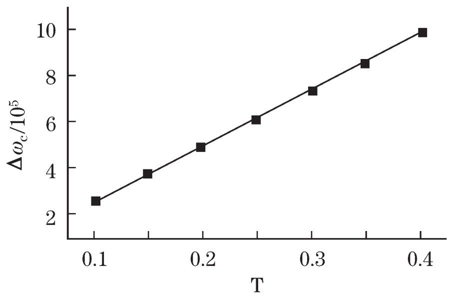

Fig. 3. $\Delta\omega_c$ as a function of T when R=0.5.

of the four fiber lasers. Parameters used in the simulation are listed in Table 1. Only initial phases, reflectivity of beam splitter, and transmissivity of FBG are control parameters that affect the injection phase-locking process. In Fig. 2, the initial phases of lasers 1−4 are $\phi_1(0)$=0, $\phi_2(0)=-\pi/6$, $\phi_3(0)=-\pi/3$, $\phi_4(0)=\pi/6$, and R=0.5, T=0.4.

From Fig. 2(a), the phase differences clearly approach a constant value within 0.001 μs, but the values are different. Figure 2(b) shows the normalized amplitude of laser 1, with an amplitude value of 2.0 ms as normalization reference. The amplitude goes through a process of damped oscillation, and approaches a constant value within 0.5 ms, a much longer time compared with phase differences. When all amplitudes and phase differences reach constant values, the fiber array can be said to have been phase-locked.

If the four fiber lasers work with the same frequency, then constant values of phase differences between any two lasers can only be $-\pi$, 0 or π, even though the initial phase differences $\phi_j(0)$ are stochastic. In Fig. 2 (a), the constant value of phase difference between laser 1 and laser 2 is $\Delta\phi_{12}=-\pi$ when $\phi_2(0)=-\pi/6$.

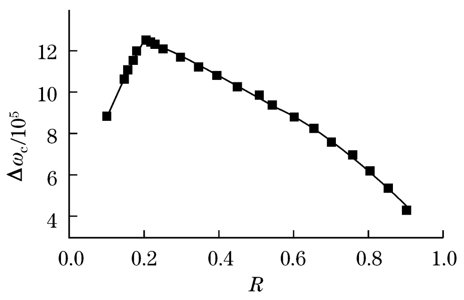

Fig. 4. $\Delta\omega_c$ as a function of R when T=0.4.

However, the constant value of phase difference between laser 1 and laser 2 is $\Delta\phi_{12}=\pi$ when $\phi_2(0)=\pi/6$. Therefore, the constant values of phase differences are related to initial phases.

If the frequency detuning $\Delta\omega$ exceeds a critical value, then $\Delta\phi_{1j}$ is an unbounded function of time. Therefore, to realize injection phase-locking of the fiber-laser array, it is necessary for the frequency detuning to be less than the critical value $\Delta\omega_c$[12]. In the simulation, $\Delta\phi_{1j}$ does not approach a constant value within 2.0 ms when $\Delta\omega$ is larger than $\Delta\omega_c$. With this law, we are able to distinguish critical frequency detuning. Figure 3 shows the relationship between T and $\Delta\omega_c$ when R=0.5. From Fig. 3, $\Delta\omega_c$ is shown to increase almost linearly with T and the slope is 2.475×10^5 Hz. Therefore, by increasing transmissivity T of the cavity reflector, the critical value $\Delta\omega_c$ can be linearly increased, which means that injection phase-locking of the fiber-laser array becomes easier. Figure 4 shows the relationship between R and $\Delta\omega_c$ when T=0.4. $\Delta\omega_c$ increases rapidly first and then decreases afterwards with the increase of R. $\Delta\omega_c$ reaches its maximum at the point R=0.21, which shows that an appropriate value of R should be optimized in order to make injection phase-locking of the fiber-laser array easier.

In this letter, we report on a new technique of mutual injection phase-locking fiber-laser array that uses a 45 degree beam splitter as coupling device. Numerical simulation on fiber laser array is carried out. Time evolutions of amplitudes and phase differences are analyzed. We find that constant values of phase differences are related to initial phases. Transmissivity of cavity reflector and reflectivity of the beam splitter should be properly optimized to make injection phase-locking easier. The work is helpful in understanding and developing an effective high power mutual injection phase-locking fiber-laser array.

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