Synchronization and coherent combining of two pulsed fiber lasers

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We demonstrate a scalable architecture for coherent combining of pulsed fiber lasers. A new method for generating synchronous pulsed fiber lasers by direct phase modulation is proposed and investigated. It is shown that phase modulated mutually coupled laser array can be a steady synchronous pulsed fiber laser source. The synchronous pulsed fiber lasers are coherently combined with an invariable phase difference of π in adjacent lasers. Neither active phase control nor polarization control is taken in our experiment.

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Recent advances have shown that fiber lasers have the capability to generate kilo-watt level output power with good beam quality[1]. Further power scaling of fiber laser is restricted in terms of thermal load, fiber damage and nonlinearity[2]. Coherent combining of many lasers can increase the overall output power and maintain the diffraction-limited beam quality[3]. Several approaches were demonstrated to scale up output power by combining multiple fiber lasers[4−7]. Most of those coherent combining architectures were used for continuous laser beams. While many applications fields such as pulsed laser illuminators often require high peak power pulsed laser, thus coherent combination of pulsed laser need to be studied. However, few reports discussed on this issue[8,9]. Nevertheless, the combined output power is still limited because of the damage to the coupling schemes with a single fiber output[8,9]. The challenges such as nonlinear effects still can not be avoided. In this case, a spatially distributed and coherent array is desired. For coherent combining of pulsed lasers, synchronous and phase-locked pulses generation is also required. In this letter, we report the experimental study on the issue of coherent combining of two pulsed fiber lasers.

Mutually coupled laser array have been studied extensively due to the possibility of practical applications of chaos synchronization to secure communication and high power laser source[10−14]. In a mutually coupled laser array, lasers are coupled with their adjacent elements by energy injection.

It is known that for a single laser, the relaxation oscillation frequency $\omega_{\rm R}$ is given[15] by

$$\omega_{\rm R} = (\delta(\gamma/\gamma_{\rm th} - 1)/\tau_{\rm f}\tau_{\rm c})^{1/2}, \tag{1}$$

where $\tau_{\rm c}$ is the cavity round trip time, $\tau_{\rm f}$ is the decay time of the upper lasing level of the doped ion, $\gamma_{\rm th}$ and γ are the threshold and the actual pump rates, δ is the fractional cavity loss per pass. It was demonstrated[15] that the laser intensity may be driven into chaotic fluctuations if the pump beam is modulated at a frequency $\omega_{\rm M}$ close to the relaxation oscillation frequency $\omega_{\rm R}$. Synchronous chaos in a mutually coupled laser array were generated by amplitude modulation of one laser in the array[11,12,15]. However, the possibility for generation of regular synchronous pulsed laser has not yet been discussed. We will show experimentally that synchronous pulsed lasers can be generated and coherently combined by phase modulation of a mutually coupled fiber laser array.

The experimental setup is shown in Fig. 1. The gain fibers are 5-m-long single Er-doped fibers. A continuous-wave (CW) semiconductor laser of 980 nm is used to

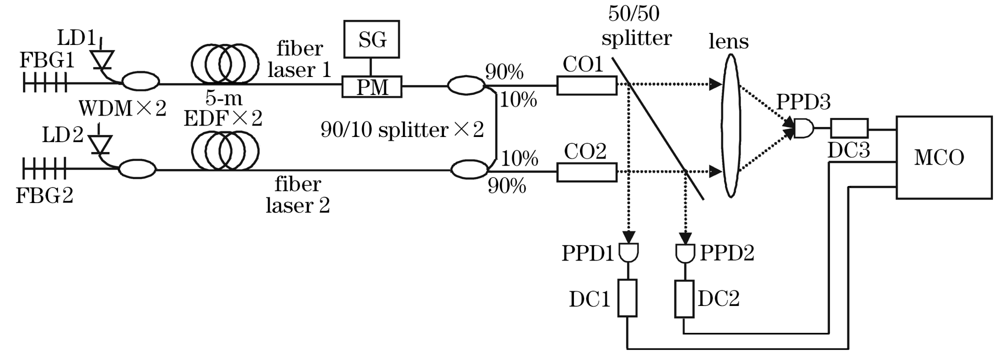

Fig. 1. Experimental setup for coherent combining of two synchronous pulsed fiber lasers. FBG1, FBG2: fiber Bragg gratings; LD1, LD2: 980-nm pump laser diodes; WDM: wavelength-division multiplexer; EDF: erbium-doped fiber; SG: signal generator; PM: phase modulator; CO1, CO2: collimators; PPD1, PPD2, PPD3: photodetectors; DC1, DC2, DC3: detection circuits; MCO: multi-channel oscilloscope.

pump the Er^{3+} doped fiber through a wavelength division multiplexer. Each laser cavity is formed by a fiber Bragg grating (FBG) ($R \sim 99\%$ with a full-width at half-maximum (FWHM) of 0.05 nm centered at the Bragg wavelength $\lambda_{\mathrm{Bragg1}} = 1549.88$ nm for FBG1 and $\lambda_{\mathrm{Bragg2}} = 1549.93$ nm for FBG2) and 4% Fresnel reflection at the output cleaved facet. Lasers are collimated and sent to free space via the collimators (CO1 and CO2). A pigtailed $LiNbO_3$ crystal phase modulator driven by commercial signal generator is placed between the doped fiber and the 90/10 splitter in laser 1. Phase modulation with certain depth and frequency can be implemented by adjusting the signal generator. The two lasers are connected by two 90/10 fiber splitters. A 50/50 splitter is located at the output port of the fiber lasers. Two photodetectors (PPD1 and PPD2) are used to measure the temporal intensity waveform simultaneously. The two laser beams are focused and combined by a lens to simulate the far-field effect. Another photodetector (PPD3) is used to measure the combined beam temporal intensity distribution. The temporal intensity waveform of individual laser beam and the combined beam can be measured simultaneously using the multi-channel digital oscilloscope. Moreover, fiber used in this experimental setup is non polarization maintained one and there is no polarization control.

In order to decide the frequency of the modulation signal, we should firstly estimate the relaxation oscillation frequency ω_{R}. The parameters are taken as follows: the cavity round trip time $\tau_{\mathrm{c}} = 33.33$ ns (because of 5-m-long fiber), the fluorescence time $\tau_{\mathrm{f}} = 11$ ms, fractional cavity loss $\delta = 0.96$. The pump current of the two lasers are both 40 mA, resulting that the value of $\gamma/\gamma_{\mathrm{th}}$ is about 1.2 (the threshold of the pump current is about 33 mA), thus the relaxation oscillation frequency is about $\omega_{\mathrm{R}} = 22.88$ kHz.

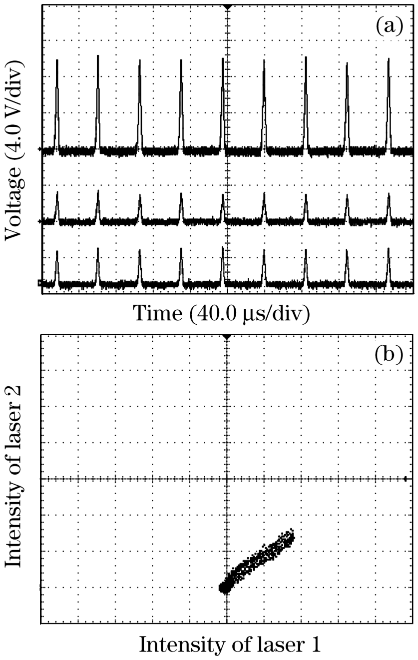

Fig. 2. (a) Temporal waveforms of two mutually coupled lasers and the combined laser beam with active phase modulation at a frequency of $\omega_{\mathrm{M}} = 23$ kHz. Middle and lower solid curves denote laser 1 and laser 2 respectively, upper solid curve denotes the intensity of the combined beam; (b) correlation plot for the two lasers.

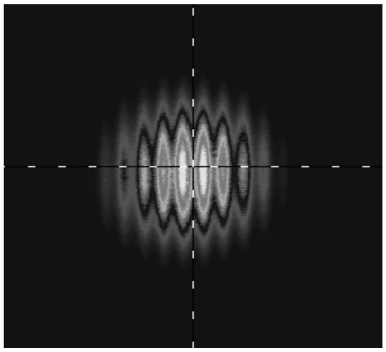

Fig. 3. Far-field intensity pattern of the combined pulsed laser beam.

The experimental results for generation of two synchronous pulsed fiber lasers are shown in Figs. 2 and 3. By adjusting the signal generator, we find that regular and synchronous pulsed lasers can be obtained when the modulation frequency is chosen to be 23 kHz, almost equal to the data calculated in foregoing paragraphs. Figure 2(a) shows the temporal waveforms of two mutually coupled lasers and the combined laser beam with active phase modulation at a frequency of $\omega_{\mathrm{M}} = 23$ kHz. The repetition rate of the two pulsed laser is also 23 kHz. The combined beam has doubled the peak power of each individual one with durations of about 2 μs. Figure 2(b) gives the correlation plot for the two individual lasers. It shows that totally synchronically pulsed fiber lasers can be obtained by phase modulation. The far-field combined beam intensity is given in Fig. 3 and the far-field spot denotes a character of out-of-phase mode. It is shown that the two pulses are also phase-locked with an invariable phase difference of π. This phenomenon is consistent with that in coupled semiconductor or solid laser arrays[16], and can be explained by the corresponding theory. It can be corrected to be in-phase mode by adding π phase shift to one of the fiber lasers.

When the modulation frequency is chosen to be far different from 23 kHz, the mutually coupled laser array will turn out to be a chaotic laser source. As Fig. 4 shows, irregular bursting and fluctuations exist in each individual laser. However, the irregular bursting and fluctuations are still synchronous. This phenomenon

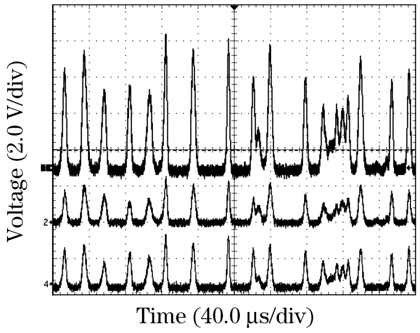

Fig. 4. Temporal waveforms of two mutually coupled lasers and the combined laser beam with active phase modulation at a frequency of $\omega_{\mathrm{M}} = 5$ kHz. Middle and lower solid curves denote laser 1 and laser 2 respectively, upper solid curve denotes the intensity of the combined beam.

was reported earlier for mutually coupled solid-state laser array[15].

The generation of the synchronous pulses can be explained as follows. The regular pulsed laser can be obtained by phase modulation at certain frequencies, for example, close to the relaxation oscillation frequency ω_{R}, which has not yet been reported by amplitude modulation[11,12,15]. Fiber laser 2 is coupled to intracavity phase modulated fiber laser 1 via the fiber splitter. The electric field in laser 2 is strongly coupled to and affected by the electric field in laser 1. Modulation of the phase in laser 1 leads to well synchronized and phase-locked pulsed fluctuations of the two laser intensities.

In summary, we demonstrate a scalable architecture for coherent combining of pulsed fiber lasers. A new method for generating synchronous pulsed fiber lasers is proposed and investigated. We find that mutually coupled laser array can be a steady synchronous pulsed fiber lasers source if the one of the laser in the array is actively phase modulated at the relaxation oscillation frequency. The synchronous pulsed fiber lasers are phase-locked with phase difference of π in adjacent lasers. They can be coherently combined. The architecture proposed in this letter is scalable because of multi-output port setup. There is neither active phase control nor power limitation induced by single port output that often exists in this passive phase control setups. We are now building a more complex system to generate and coherently combine more than three pulsed fiber laser beams.

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