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High Power Pulse Laser Reflection Sequence Combination with a Fast Steering Mirror *

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We propose and demonstrate a new approach for a high power pulse laser reflection sequence combination with a fast steering mirror (FSM). This approach possesses significant advantages for lasers combining with a variety of output power, wavelength, pulse duration, repetition rates and polarization. The maximum number of laser routes participating in combination principally depends on the FSM's adjustment time of the step response, lasers' repetition rates and pulse duration. A proof-of-principle experiment is performed with two 2-kW level pulsed beams. The results indicate that the combined beam has an excellent pointing stability with rms pointing jitter ∼8.5 μrad. Meanwhile, a high combining efficiency of 98.6% is achieved with maintaining good beam quality.

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High average output power and high beam quality lasers, which are available to be coupled into fibers, are extremely in demand in laser processing.[1] Nevertheless, owing to various restrictions including thermal effects, residual distortions and nonuniformity of pump light distribution, it is difficult to obtain a single laser oscillator scaled to very high power output while maintaining good beam quality. To overcome these difficulties, the beam-combining technique has been considered to be an effective and outstanding approach for achieving high average power laser output.[2,3] The beam combination can generally be classified into two categories: coherent beam combining (CBC) and incoherent beam combining (IBC). In CBC, ideally, for the case of N lasers, the output power of the combined laser can be N times that of a single laser, while the on-axis intensity is scaled N^2 times. In practice, the phases of laser arrays are extremely vulnerable to mechanical vibrations and thermal drifts.[4] Rather precise and complex controlling is necessary to keep the phases of laser arrays.[5,6] Usually, the less-than-unity fill factor of near-field intensity leads to side lobes at the far field, reducing the total energy utilization.[7] In IBC, it is more achievable for multi-lasers to be combined with less requirements on the spectrum and phases. The main approach routes of traditional IBC contain side-by-side beam combining (SSBC), polarization beam combining (PBC), and wavelength beam combining (WBC).[8−11] Based on PBC, Bammer *et al.* achieved a combined laser with output power of 10.5 W and overall optical efficiency of 73%. The efficiency loss is mainly due to the PBC's sensitivity to the polarization degree of laser beams.[12] Using reflecting volume Bragg gratings in cascaded geometry, Sevian *et al.* demonstrated a WBC combined power ∼ 950 W with five lasers emitting from 1062.08 to 1064.55 nm, having a combining efficiency of 93%, which was limited mainly by the material and cross-talk losses.[13] For the investigation of pointing stability, a double-wavelength WBC implemented by Xia *et al.* reached a root mean square (rms) pointing jitter ∼23.51 μrad.[14] Liang *et al.* reported the high average power spectral beam combination employing volume Bragg gratings, and achieved the combined power of 856 W and combining efficiency of 73.7% with $M_x^2 \sim 7.9$ and $M_y^2 \sim 2.7$. However, the beam quality and diffraction efficiency after diffraction of the bulk Bragg grating significantly deteriorates with the increase of the diffracted beams' spectral width.[15] Recently, a refraction displacement pulse sequence combining apparatus was reported by Xu *et al.*, achieving the combined output power of 1395 W, the diffraction limited times β of 7.6 and combining efficiency of 98.4%. However, it is mostly limited by the complexity of structure.[16]

In this Letter, we present a high power pulse laser reflection sequence combination (PRSC) with a fast steering mirror (FSM). With this technique, we can achieve sequential coaxial combination of laser pulses with high pointing stability. The beam quality of the combined beam is comparable to those of the beamlets. This approach is potentially adapted to the ma-

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jority of types of pulsed lasers, benefiting from its simple and compact construction as well as the insensitivity to spectral, phase and polarization degree. In a proof-of-principle experiment, we implement two 2-kW level pulsed beams for addition. The combination efficiency is up to 98.6% with good beam quality of $\beta \sim 4$ and excellent pointing stability of rms pointing jitter ~8.5 μrad.

As the important apparatus of PRSC, an FSM commonly consists of piezoelectric (PZT) actuators, a quartz mirror, a flexure support system and a servo control system. PZT actuators are mainly applied to operate flexure supported FSM. Quartz mirror, coated high-damage-threshold high-reflection film, acts as the reflector. Flexure support system is attached to the piezoelectric (PZT) actuators and quartz mirror, allocating compliance and constraint of mirror's motion among multi-degrees of freedom. A servo control system, including sensors or sensing systems, aims to control the movement of the FSM.[17]

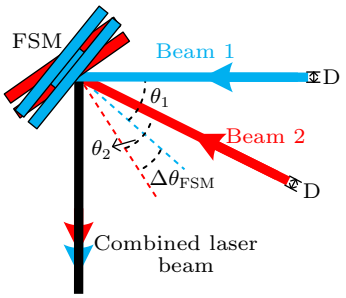

Fig. 1. Schematic diagram of the PRSC with an FSM for two pulsed beams.

For the FSM, actual angle status of reflector can be reciprocated between different states, which is the main property to achieve PRSC. As an example, two laser beams operate at the same repetition rate, while having two different incidence angles θ_1 and θ_2 onto the FSM reflector, as shown in Fig. 1. By accurately synchronizing between the actual angle status of reflector of FSM and the arrival time of the laser pulses, beamlet 1 is reflected by the FSM at state 1 and beamlet 2 is reflected by the FSM at state 2, alternatively. When beamlet 2 is incident on the same position of the FSM at state 2, it is shifted to the reflected path of beamlet 1. By controlling the status of FSM, the incident angle of the beamlets, and the incidence point of two beamlets at the reflector, the directing of beamlet 2 after reflection can exactly match with that of beamlet 1. Following this principle, using $(N-1)$th state of the FSM, the optical paths of Nth pulsed laser overlaps with those of the previously combined $N-1$ beamlets.

In our experiment, the adjustment time of the step response $t_{\rm FSM}$ of the FSM is able to reach 1.5 ms and the laser repetition rate f is set to 80 Hz. Therefore, this FSM has an ability to combine six pulse lasers at most.

In a proof-of-principle experiment, we preferentially add two high power pulsed beams. The schematic layout of the combining setup of two similar beams is illustrated in Fig. 2. Both the lasers are homemade Nd:YAG pulsed laser oscillators at 1064 nm with spectral width of 0.15 nm, operating at a repetition rate of 80 Hz with pulse width of 500 μs. With beam shaping, the sizes of beam spots D are both 12 mm(W)×60 mm(L) on the near-field and the included angle $\Delta\theta_0$ between them is about 4.7 mrad. Through the role of the beam expanding system, the sizes of laser spots D' are enlarged to 56 mm (W) ×60 mm (L), and the angle $\Delta\theta_1$ between the laser beams is reduced to about 1 mrad. The beam expanding system consists of two fused quartz cylindrical lenses labelled as L1 and L2 as shown in Fig. 2. L1 is a plane-concave cylindrical lens with a radius of −75 mm. L2 is a plane-convex cylindrical lens having a radius of 350 mm. The FSM is able to work at 160 Hz when the commuting angle is 1 mrad. To make sure the synchronization of the FSM and the pulsed laser, a signal generator (Keysight 33600A) is used to generate the trigger signal and sends it to the synchronizing device. The synchronizing device then sends three series of triggering pulses to trigger the two lasers and the FSM. Synchronization accuracy of the synchronizing device is about 2 μs. The pulsed beamlet 2 is delayed by 6250 μs with respect to beamlet 1.

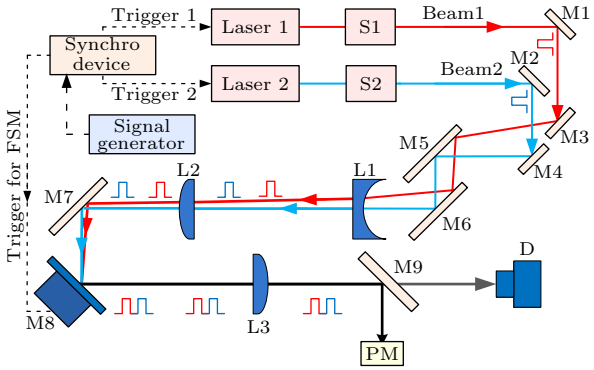

Fig. 2. Schematic layout of PRSC for two pulsed lasers. S1, S2: beam shaping device, M1–M9: HRs at 1064 nm, M8: fastened on the linear motors of the FSM, L1–L3: HTs at 1064 nm, PM: power meter, D: charge coupled device cameras.

The reflector is mounted on the flexure support system which is attached to the piezoelectric (PZT) actuators of the FSM. To prevent the jitter of the beam direction resulting from the angular repeatability of FSM, we chose excellent piezoelectric (PZT) actuators with positional repeatability of <45 μm. To improve reflectivity of the FSM reflector, the light incident surface of the reflector is all high-reflection coated at 1064 nm. The beamlet 1 arrives at the reflector of the FSM at state 1. The incident angle is 45°. Then, beamlet 2 arrives at the same position of the FSM reflector at state 2. The discrepancy of incidence angle between two laser beams is less than 1 mrad and the optical path of beamlet 2 coincides with beamlet

1 after reflection by the FSM reflector.

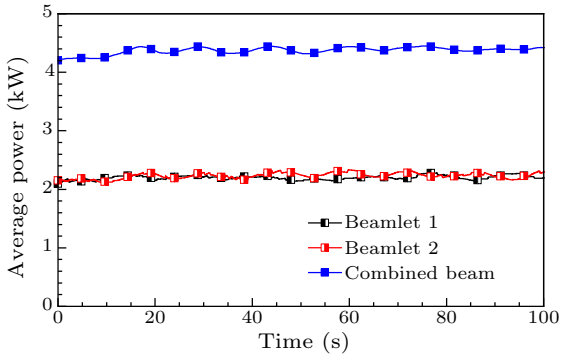

Fig. 3. Measured laser output powers versus time.

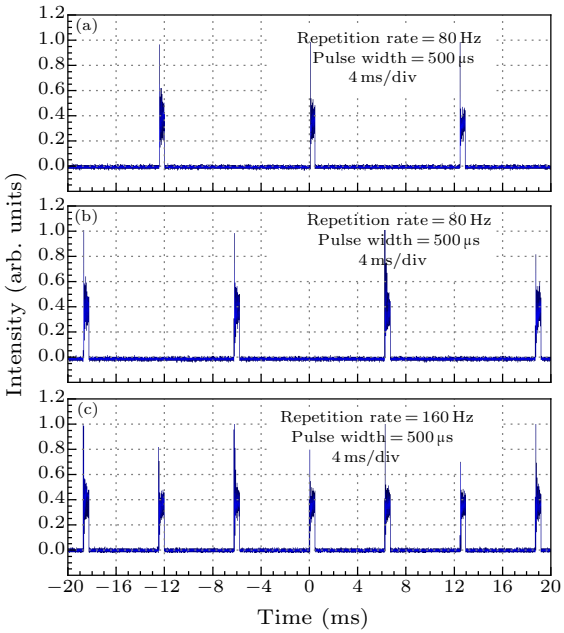

Fig. 4. Typical oscilloscope traces of pulse train: (a) beamlet 1, (b) beamlet 2, and (c) combined beam.

Before the combination of two pulsed lasers, we measure the average powers of beamlets 1 and 2 with an Ophir power meter, which are 2198 W and 2232 W. After the combination, we obtain a combined pulse beam with an average output power of 4371 W, corresponding to a combining efficiency of 98.6%. As we know, this is the highest combining efficiency for the QCW pulse beam combination reported so far. The combined power fluctuation is measured to be ±3% over 100 s, as shown in Fig. 3. The pulse train of the laser is detected by a photoelectric converter with frequency bandwidth of 300 MHz and displayed by an oscilloscope (Tektronix DPO3034). Typical oscilloscope traces of pulse train are displayed in Figs. 4(a)–4(c) for beamlets 1 and 2, and the combined beam, respectively. Both the repetition rate and the pulse width for the two pulsed beamlets are 80 Hz and ∼500 μs, as shown in Figs. 4(a) and 4(b). The corresponding oscilloscope trace of the combined beam is exhibited in Fig. 4(c), where the first pulse in a cycle is from beamlet 1 and the second pulse in a cycle is from beamlet 2. After combining, the repetition rate of the combined beam is doubled to be 160 Hz, and the time interval between beamlets 1 and 2 is ∼6250 μs as anticipated.

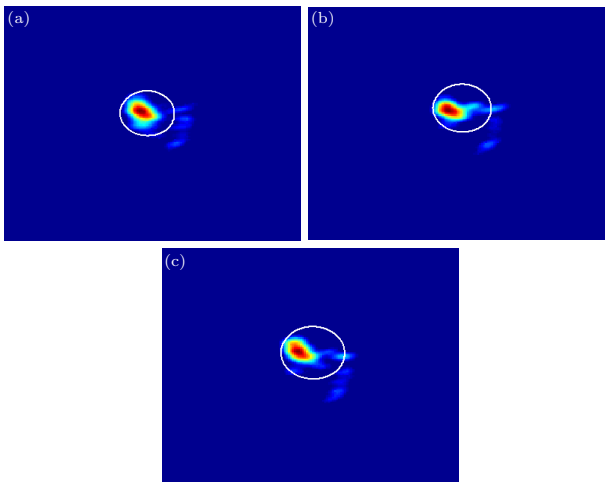

Fig. 5. Typical far-field beam intensity distributions: (a) beamlet 1, (b) beamlet 2, and (c) combined beam.

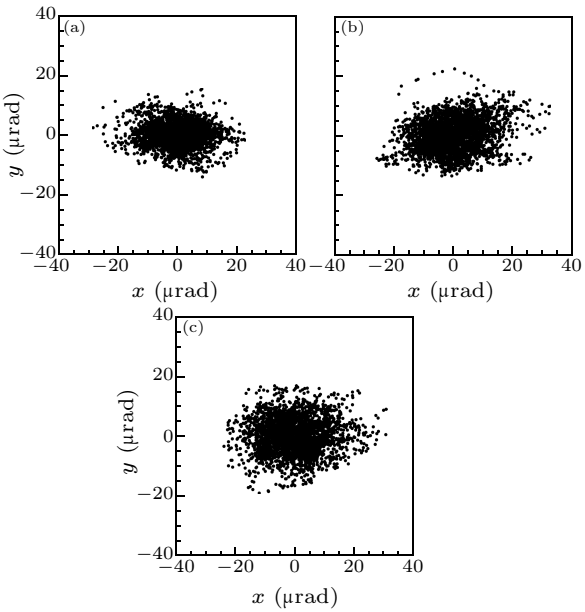

Fig. 6. Measured centroid distributions of beam spots for the far field: (a) beamlet 1 (σ_X = 7.2 μrad, σ_Y = 3.8 μrad), (b) beamlet 2 (σ_X = 8.5 μrad, σ_Y = 5.4 μrad), and (c) combined beam (σ_X = 8.5 μrad, σ_Y = 5.7 μrad).

The laser beam intensity distribution is measured by a charge-coupled-device (CCD) camera (MV1-1312D). Figures 5(a)–5(c) show the typical far-field beam intensity distributions of beamlets 1, 2 and the combined beam. Diffraction limited times β are calculated to be 3.5, 3.7 and 4. Clearly, the beam quality of the combined pulse is slightly more degraded than these of beamlets 1 and 2, while still retaining a good beam quality. The rms values of the pointing jitter for beamlet 1 are σ_X = 7.2 μrad and σ_Y = 3.8 μrad (Fig. 6(a)). The rms values of the pointing jitter for beamlet 2 are σ_X = 8.5 μrad and σ_Y = 5.4 μrad

(Fig. 6(b)). The temporally variable thermal expansion of the laser crystal and mechanical vibrations disturbing laser sources are the main factors of the jitter of beamlets 1 and 2.[18] The rms values of the pointing jitter for the combined beam are $\sigma_X = 8.5\,\mu$rad and $\sigma_Y = 5.7\,\mu$rad (Fig. 6(c)). The pointing jitter of the combined beam should be caused by the vibration of combining device and air turbulence by the high-speed reciprocated reflector, which leads to the degradation of the combined beam quality. Nevertheless, the pointing jitter of this combined beam is improved to be at least 2.7 times more than that in Ref. [14], indicating its high pointing stability. Moreover, the beam quality and pointing stability can be further enhanced using an adaptive optics technique.

In summary, we have proposed and demonstrated a compact high efficiency and high pointing stability reflected pulse combining approach with an FSM. In the proof-of-concept experiment, we have successfully combined two 2 kW-level pulsed lasers and achieved a 4 kW-level laser output with high combining efficiency of 98.6%, good beam quality of $\beta \sim 4$. Particularly, an excellent pointing stability for the combined beam is obtained with rms pointing jitter $\sim$8.5 μrad. Compared to other combining approaches, PRSC is able to combine high power pulsed lasers with high pointing stability without introducing further complexity. It is also a potential approach to scale higher output power with good beam quality by the beam combination of multiple lasers.

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