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Using harmonic beam combining to generate pulse-burst in nonlinear optical laser

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The ultrashort lasers working in pulse-burst mode reveal great machining performance in recent years. The number of pulses in bursts effects greatly on the removal rate and roughness. To generate a more equal amplitude of pulses in burst with linear polarization output and time gap adjustable, we propose a new method by the harmonic beam combining (HBC). The beam combining is commonly used in adding pulses into the output beam while maintaining the pulse waveform and beam quality. In the HBC, dichroic mirrors are used to combine laser pulses of fundamental wave (FW) into harmonic wave (HW), and nonlinear crystals are used to convert the FW into HW. Therefore, HBC can add arbitrarily more HW pulses to generate pulse-burst in linear polarization with simple structure. The amplitude of each pulse in bursts can be adjusted the same to increase the stability of the burst, the time gap of each pulse can be adjusted precisely by proper time delay. Because HBC adds pulses sequentially, the peak power density of the burst is the same as each pulse, pulses can be combined without concern of back-conversion which often occurs in high peak power density. In the demonstration, the extendibility of HBC was verified by combining two beams with a third beam. The combined efficiency rates were larger than 99%, and the beam quality of each beam was maintained at $M^2 \approx 1.4$.

Keywords: pulse-burst, beam combining, nonlinear optics

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1. Introduction

The great precision reached by ultrashort lasers working in ultrashort pulse-burst[1] provides new machining regimes of structuring rate and surface quality.[2] Research on the removal rate and surface roughness affected by the number of pulses in a burst[3] reveals the optimum point of two[4] or several[5] pulses for different materials.[6] With pulses added into the burst, lasers perform better than a single pulse with the same average power,[4,5] but the performance of pulse-burst mode drops when the burst contains too many pulses.[7] The process of laser pulse-induced ablation is considered in two steps.[8] The thin layer on the surface absorbs the energy of the laser and ablates into plasma with a shock wave last nanosecond, in the next step, the plasma with particle around the processing area shield the following laser pulses and decrease the ablation rate.[6,7] Since pulse-burst is generated by pulse-picker such as electro-optic devices, the amplitude of pulses in the burst is not constant, especially when the last pulse is more intense,[1,3,5] and the repetition rate of pulses is fixed and determined by the oscillator. To push further the application of burst mode lasers, a new approach is needed for meeting more processing requirements of pulses in amplitude and repetition rate adjustable.

Different from the traditional way of selecting pulses, adding new pulses into the burst provides a possibility to make bursts more adjustable. Beam combining (BC) is a practical approach to increase the power by combining pulses of different laser beams. In BC, the beam quality is maintained by reducing the burden of the thermal loads on a single aperture.[9,10] Besides, combining several pulses into a burst can achieve higher output average power without increasing the peak power density.[7] Especially in nonlinear optical (NLO) lasers, a high peak power density can cause back-conversion and reduce efficiency,[11] the time gap between pulses also can avoid the back-conversion. So NLO with BC is suitable for burst mode lasers.

Traditionally, various methods are utilized in BC: coherent beam combining (CBC), spectral or wavelength beam combining (WBC), polarized beam combining (PBC), and time-multiplexing beam combing (TBC). CBC demands the phase of each aperture beam to maintain the interference in the far field, which is widely used in single wavelength high power lasers.[10,12–14] But CBC demands active devices to precisely control the phase of each beam to ensure the interference in far-field. WBC uses the characteristics of the refractive index changed by wavelength, combining beams with multiwavelength lasers from different directions into one aperture.[15,16] Due to the spectral width of WBC, the application of WBC for certain narrow width is limited. PBC is commonly used in nonlinear laser generation, combining two beams with dif-

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ferent polarization using a polarization coupler,[17,18] so wave planes are utilized to change and combine more beams in PBC. TBC adds laser pulses sequentially into the output, increasing the repetition rate and average power, but the peak power of each pulse remains equal to each single-aperture beam.[19] TBC also is utilized in nonlinear optical lasers, with active devices such as acousto-optic,[20] and liquid crystal[21] combining beam pulses. However, the beam number of TBC is limited by these optical effects and the generally low damage threshold of these devices.

We propose in this article a new method for pulse-burst nonlinear optical lasers with harmonic beam combining (HBC). In HBC, dichroic mirrors are used to combine laser pulses of fundamental wave (FW) into harmonic wave (HW), and nonlinear crystals are used to convert the FW into HW. Therefore, HBC can add arbitrarily more HW pulses to generate pulse-burst in linear polarization with simple structure. The amplitude of each pulse in bursts can be adjusted the same to increase the stability of the burst, the time gap of each pulse can be adjusted precisely by proper time delay. Different from the traditional BC methods, HBC is designed to combine and adjust pulses of beams with all-passive devices and generate monochromatic laser output of harmonic wave with linear polarization. The main part of HBC is simple and easy to extend.

Based on the method of HBC in pulse-burst mode, we successfully demonstrated in principle by combining up to 3 beams with similar pulse amplitude and time delay into one pulse-burst beam with a high combination efficiency of 99.39%, and beam quality was maintained at $M^2 \approx 1.4$. The extendibility of HBC was verified by adding a third beam into the first combined two beams.

2. Methods

In this section, we introduce the constituent part of the HBC of structure and the harmonic wave generation process. Also, how to ensure the efficiency of converting and combining is discussed.

2.1. Harmonic beam combining

To combine multi-aperture of laser sources, especially in further scaling the output power in high-power lasers, multi-source is more convenient to control the amplitude and time delay of each pulse generated. However, to ensure synchronization and pointing stabilization between beams, the complexity is increased. This might be worthwhile and can be overcome in future. On the other hand, single-source has better repetition stability than multi-source and costs less. So, we chose to split one FW laser into three in our principal demonstration. The main idea of HBC is shown in Fig. 1. The initial FW is divided into three pulses with time delay τ, which can be controlled by a proper delay path between each beam. In the perspective of repetition, the intra-burst (between pulses) repetition rate is determined by τ as designed, and the inter-burst (between bursts) repetition rate is equal to the light source we use. The amplitude of each FW pulse is set by the split ratio of the beam splitter, or can be adjusted by replacing the beam splitter with a half-wave plate followed by a polarizing plate. The amplitude of each beam can be adjusted by the rotation of the have-wave plate. On the other hand, the second approach needs additional half-wave plates for rotating the transmitted parallel polarization beam into vertical polarization to maintain the same polarization of each beam. In our principal demonstration of HBC, the simpler beam splitters are used to split FW pulses roughly.

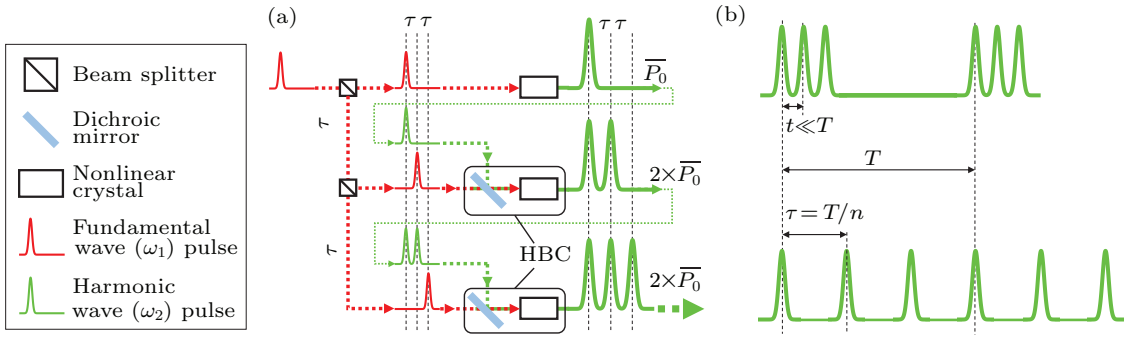


Fig. 1. (a) Schematic diagram of HBC. The red pulses represent the FW, while the green pulses are the HW. (b) HBC outputs of the pulse burst or repetition rate increasing. τ is the time delay between beams. T is the time gap between pulses of each beam. Pulse-burst has a much shorter τ than T.

When fundamental wave passes through the nonlinear crystal, FW is converted into HW. Then HW is combined with the next FW beam pulse, followed by a second crystal to convert the second FW into HW, therefore generating the pulse-burst with the average power of HW output increased. With proper set time delay τ of each incident FW beam, pulse-burst ($\tau \ll T$, T is the pulse gap of single beam) and repetition rate increasing ($\tau = T/n$, $n = 1, 2, \ldots$) can be achieved. As we use dichroic mirrors to coaxially combine FW and HW beams, only passive components are utilized, and this simple setup ensures the arbitrary beams can be added easily. In pulse-burst or repetition rate increasing mode, the HW pulses pass

through crystals unchanged because they usually need a much higher peak power density for frequency back-conversion to the FW.[11] The output average power of pulse-burst can be increased by adding HW pulses with HBC, but the peak power density of output is maintained. In a nutshell, the HBC can add arbitrary laser beams into pulse-burst all passively without precise phase controlling or polarization modulation.

2.2. Second harmonic generation

The FW laser of 1064 nm of each beam we use has a repetition rate of 10 kHz, and the measured pulse duration of full width at half maxima (FWHM) is about 337 ps, with a beam quality of $M^2 \approx 1.3$. Waveforms are shown in Fig. 2.

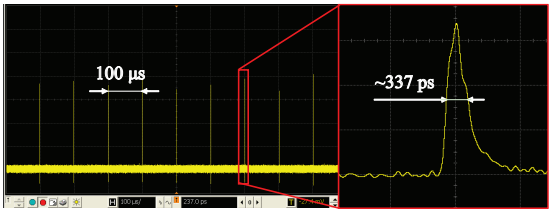


Fig. 2. The waveform of the FW laser of 1064 nm. Laser pulse duration is much shorter than pulse interval.

The green laser such as the second harmonic wave 532-nm laser from the second harmonic generation (SHG) of the near-infrared 1064-nm laser, has a broad application in manufacturing,[22] sensing,[23] and medical treatment.[24] The pulse-burst mode operating 532 nm also can be used in detection.[25] To generate a 532-nm laser, the type-I phase matched LBO (LiB_3O_5) crystal[26] is commonly used, because of the high damage threshold and wide acceptance angle.[27,28]

We possess 3 LBO crystals of 20, 30, and 40 mm long with the same transverse size of 4 mm×4 mm. Since the FW laser operates in the Gaussian beam, to maintain the beam quality of HBC, the waist of each beam should be matched in the same position on the light axis, and the beam radius of each beam incident into each LBO crystal is different with divergence. The beam radius and corresponding power density are listed in Table 1. So, we set the shortest crystal as LBO 1st and the longest crystal as LBO 3rd in the experiments. The length of the crystal covers the power density drops due to the divergence by the Gaussian beam propagating, ensuring the high efficiency of SHG. If the beam is collimated with no divergence or beam waist imaged at each crystal with similar size, then the requirement of length of each crystal is non-essential.

Table 1. SHG Parameters of each LBO Crystals.

LBO	Length (mm)	Beam radius (μm)	Peak power density (MW/cm^2)
1st	20	144.9	526.24
2nd	30	197.8	253.54
3rd	40	272.3	143.94

2.3. Converting and combining efficiency

Each of the beams is measured passing through the entire HBC system individually with 1064-nm light from other beams blocked. These results represent the potential output power or efficiency (eff.) in the HBC. The power results are plotted in Fig. 3.

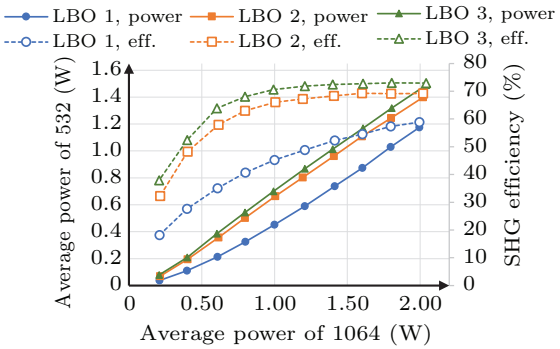


Fig. 3. The SHG efficiency of all the 3 LBO crystals measured by the power of the 532-nm laser *versus* the injected 1064-nm laser.

As our method combines the process of nonlinear optics (NLO) with BC, this might push forward the power scaling of pulse lasers generated by NLO effects. This combination has the potential for being added arbitrarily as needed power with single wavelength and linear polarization output.

To achieve HBC with high efficiency, not only the FW (1064 nm) should convert into HW (532 nm) with high converting efficiency, but also the HW should pass the rest nonlinear crystals without loss. The back-conversion of HW back to the FW should be avoided by limiting crystal length and the peak power density in the crystal. In Ref. [11] the back-conversion occurred in a 10-mm thick LBO with a peak power density larger than 4 GW/cm^2. To achieve a high SHG efficiency, we incident FW with several hundreds of MW/cm^2 into LBO.[29] On the other hand, the residual FW reflected by two mirrors (both coated with HR@532 nm and AR@1064 nm) might become a signal for optical parameter amplification (OPA) pumped by HW. But as the threshold for the OPA in LBO is usually up to several GW/cm^2,[30] the OPA can be avoided by the peak power density of the combined pulse-burst remains the same as the single pulse separated in time. So, the significant gap in the power density demand between SHG and OPA allows us to implement our method with high efficiency.

The key in our method HBC is that each laser pulse injects into the nonlinear crystal with a designed time delay, as τ shown in Fig. 1 in the form of multiplexing. As the pulse duration is subnanosecond, much less than the pulse interval of 100 μs, the time delay τ of each beam can be set by proper propagating length, such as 800 mm for $\tau \approx 2.7$ ns. The HW and the FW of different beams are separated in time when passing through the crystal, as shown in Fig. 1, so the interconversion of HW and FW of different beams is avoided even

with perfect phase matching conditions in angle and temperature. As a result, the HW pulses can pass through the crystal nearly without loss, while the next FW pulse can generate HW pulses with high efficiency.

3. Experiments and results

In the principal demonstration of HBC, we verify the practicability of combining the pulses of 532-nm lasers into bursts by HBC without decreasing beam quality. Firstly, we need to verify that the 532-nm laser passes through another LBO nearly without loss. Secondly, we build two beams HBC to demonstrate the combination efficiency. Finally, we add the third beam to verify the extendibility of adding more beams. Results of power, beam quality, and waveforms are measured and analyzed.

3.1. Basic verification

To verify the SHG 532-nm laser passing through the following LBO crystals without loss in the experiment, we inject the 532 nm generated by LBO 1st into another LBO. All the crystals are well-mounted in ovens for perfect phase matching. The peak power density of the 532-nm laser was about 526 MW/cm^2. We then measure the power and beam quality of the laser that passes through the second LBO. The power remains at 1.17 W without back-conversion. The beam quality M^2 remains $M_x^2 = 1.27$ and $M_y^2 = 1.15$ almost the same as without passing through the second LBO. The test setup is shown in Fig. 4.

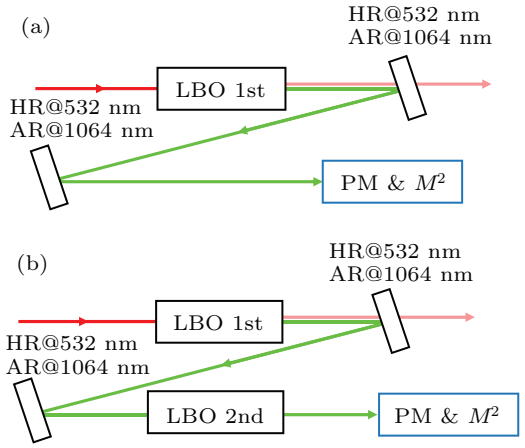


Fig. 4. Measurements of the power and M^2 of 532-nm laser generated by the first LBO compared with passing through the second LBO. (a) The laser measured without LBO 2nd. (b) The laser measured with LBO 2nd. PM: power meter. M^2: beam quality M^2 analyzer.

3.2. Two and three beams combining

As the laser is generated in Gaussian-type light, the pointing direction, waist position, and divergence angle of each beam should be matched to minimize the decrease in beam quality. By adjusting two mirrors between crystals, the optical pupil and axis of each beam can be combined coaxially into one beam, as the light path and the spot shown in Fig. 6(e). We evaluate the combining efficiency η_c by the ratio of combined power P_c to the sum of all individual output powers P_i

$$\eta_c = \frac{P_c}{\sum P_i} \tag{1}$$

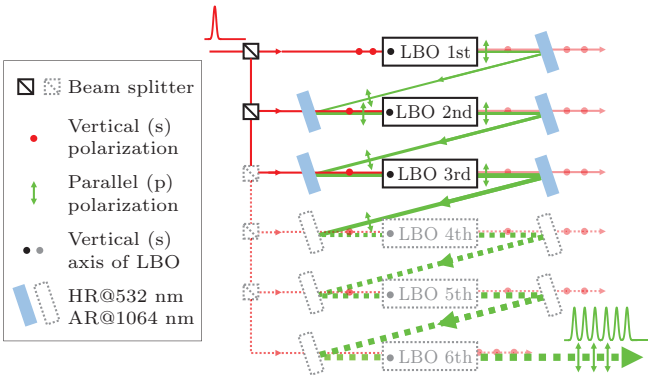


Fig. 5. The polarization status of each laser in HBC. The FW 1064-nm beams are vertical (s) polarization. The HW 532-nm beams are parallel (p) polarization. Mirrors are all coated with HR@532 nm and AR@1064 nm. Dashed graphs are more HBC units that can be added.

The power, efficiency η_c, and beam quality M^2 of each laser and the total power of combined two and three beams of lasers we measured are listed in Table 2, spot images and beam quality M^2 are shown in Fig. 6. The acquisition rate of beam analyzer is about 30 fps with 7 ms–8 ms exposure time. Since the repetition rate of bursts are much higher than our acquisition rate, the spots we obtain can be considered as long exposure shot or an accumulation of tens of bursts. To achieve better uniformity of combined beams, we control the temperature of each crystal oven to obtain the equalized power of each beam similarly in about 1.1 W. Efficiency of each beam is represented in nonlinear converting efficiency while the efficiency of combining is calculated with the sum of each beam. All spots are captured by the same light path as the light might travel during combination, especially the first beam travels through all crystals, as shown in Fig. 6(a). As considering the attenuation of non-fully reflection or transmission of mirrors, the overall efficiency defined by output HBC power divided by the total input fundamental wave, is 57.48% of two beams combining, while 61.44% of the three beams combining that we obtained in our experiment.

Table 2. Power, efficiency, and beam quality of HBC.

Beam (s)	P_i or P_c (W)	η_c	M_x^2	M_y^2
1st	1.11	–	1.27	1.15
2nd	1.05	–	1.20	1.12
3rd	1.13	–	1.16	1.08
1st + 2nd	2.15	99.54%	1.43	1.28
1st + 2nd + 3rd	3.27	99.39%	1.44	1.42

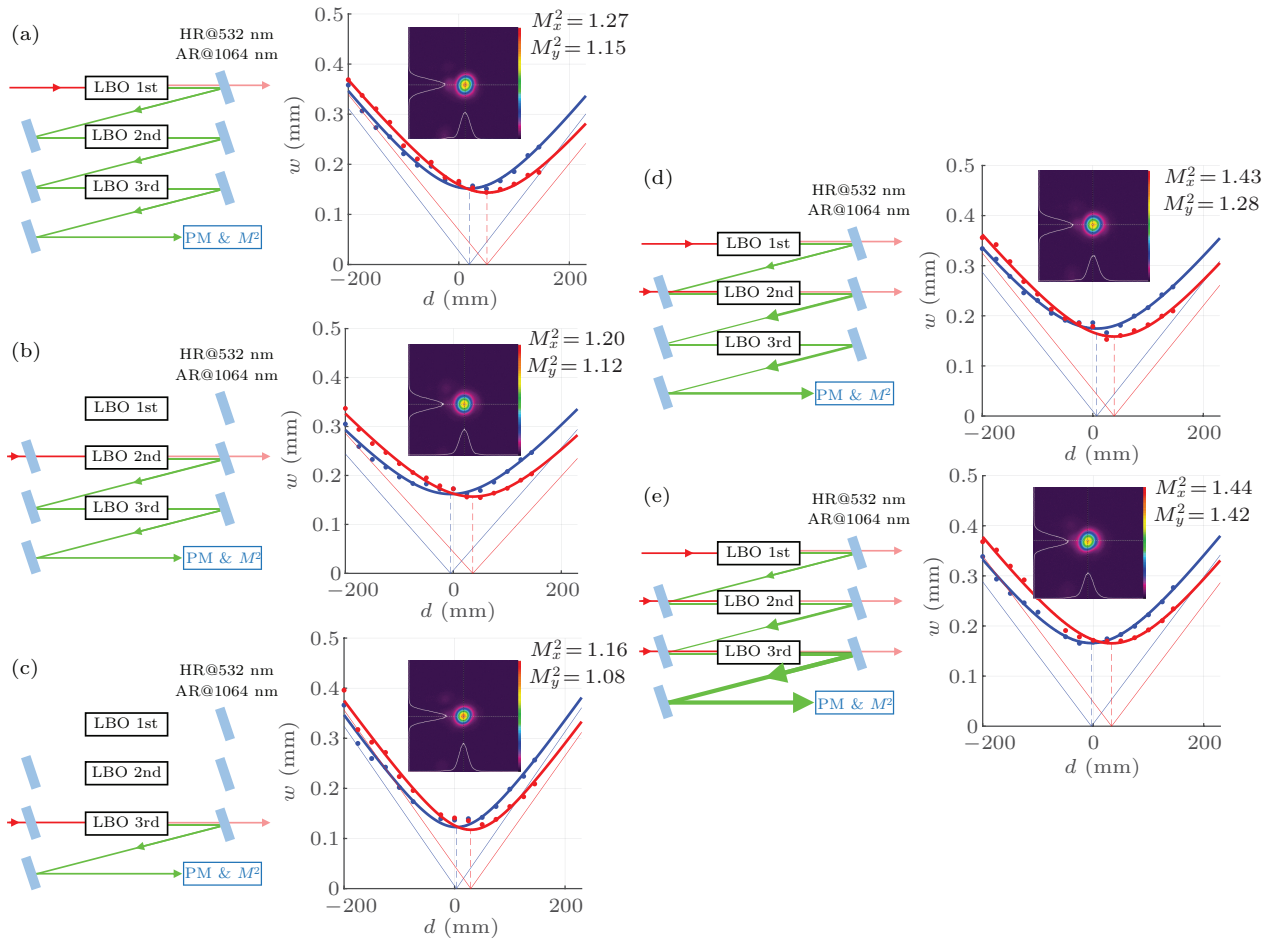


Fig. 6. The light path of HBC and beam quality of each single and combination of laser beams. (a) Only the 1st laser. (b) Only the 2nd laser. (c) Only the 3rd laser. (d) Combination of the first two laser beams. (e) Combination of 3 laser beams. PM: power meter. M^2: beam quality M^2 analyzer.

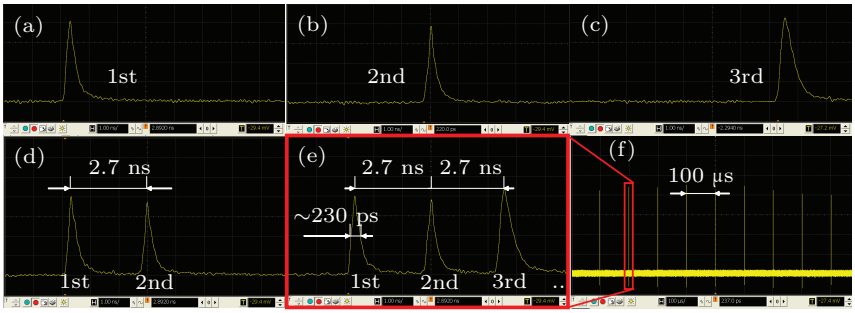


Fig. 7. The pulse waveforms of each single and combined pulse-burst laser. (a) Only the 1st laser. (b) Only the 2nd laser. (c) Only the 3rd laser. (d) Combination of the first two laser beams. (e)–(f) Combination of 3 laser beams.

As the beam quality M^2 data shows, the combination process has a certain influence on the data of M^2, the beam quality of combined beams is a little larger than individual beams. Due to the waist position mismatches of each beam, the waist of the combined beam is larger than the waist of each beam measured individually. This influence can be minimized by collimating the beam into parallel light or precisely imaging each beam waist into the same position. On the other hand, the M^2 of every single beam is around 1.2, and is measured after traveling through the same entire HBC system, including all crystals and mirrors. So, the HBC has nearly no influence on the beam quality.

With the time delay $\tau \approx 2.7$ ns is similar between each pulse in burst, the output repetition rate of the burst is 10 kHz. The waveform is shown in Fig. 7. The full width at half maximum (FWHM) pulse duration of pulses are around 230 ps.

As a result, the output power of the laser is tripled in HBC but demands no specific polarization modulation in the entire system. Besides, there is no limitation on the number of lasers to be combined, it can be easily expanded by adding dichroic mirrors and nonlinear crystal after the output with the simple setup as shown in Fig. 5. The total average power of the output laser can be significantly increased regardless the laser generating limitation of a single laser system.

4. Conclusion and perspectives

We propose a new method of pulse-burst by HBC in this article. A principal demonstration of HBC burst output with a monochromatic 532-nm laser in linear polarization was achieved by combining a 3pulse burst mode with similar amplitude and time delay we adjusted. The high combination efficiency of 99.39% and beam quality at $M^2 \approx 1.4$ of the combined beams is obtained. The back-conversion of the HW was avoided by temporal separation of pulses and maintaining of peak power density below the threshold of OPA. The extendibility of this method was verified in the experiment by adding the third beam into the firstly combined two beams.

In our simple demonstrating experiment, extra temperature control of crystal oven and optical delay costs less but can be modified in future by multiple light sources with elegant adjustment with electro-optical devices. Besides, the realization of multi-aperture laser source and time delay can be implemented more straightly by utilizing more laser sources and both amplitude and time delay can be precisely controlled electrically, also a higher output average power is generatable. Other than burst mode or repetition rate increasing output, the time delay could even be set to zero to combine pulses into larger energy pulses as needed.

We believe HBC can be further used in many other pulse NLO process laser systems with wavelengths converted, not only in SHG 532-nm laser systems strictly, to generate a higher output power without sacrificing efficiency or beam quality. The HBC brings excellent potential for a new method to generate pulse bursts and combine lasers.

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