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Authors
Zhou, Tong
Du, Qiang
Sano, Tyler
et al.

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Two-dimensional combination of eight ultrashort pulsed beams using a diffractive optic pair

Tong Zhou,* Qiang Du, Tyler Sano, Russell Wilcox, and Wim Leemans

Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, California 94720, USA

**Corresponding author: tongzhou@lbl.gov*

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We demonstrate, to the best of our knowledge, the first two-dimensional diffractive beam combination for ultrashort pulses—a highly scalable technique capable of using a diffractive optic pair to combine large arrays of ultrashort pulsed beams. A square array of eight 120 fs pulsed beams from eight fiber outputs is coherently combined into one beam using the diffractive combiner. The experimental results show that the combined pulse preserves the input pulse width and shape, and the combining efficiency is measured to be close to the limit of the manufactured diffractive optic. An analysis shows that the combining loss due to uncompensated temporal and spatial dispersions is negligible. © 2018 Optical Society of America

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In high power ultrafast fiber laser systems, detrimental nonlinear effects, due to small mode area and long propagation length of amplified pulses, result in peak power limitations and, thus, put constraints on achievable pulse energies. In state-of-the-art fiber-chirped pulse amplification systems [1], maximum pulse energies are limited to the millijoule level [2], which is orders of magnitude lower than the required energies for high energy applications, such as laser-plasma acceleration [3]. Existing coherent beam combination techniques for ultrashort pulses provide a solution for scaling up pulse energies by combining beams from parallel fiber apertures, using an array of dielectric or polarizing beam splitters [4–6]. In these techniques, the number of beam splitters scales with the number of apertures to be combined, resulting in spectral loss and dispersion imbalance, as well as system instability, in the case of combining large numbers of fiber apertures.

On the other hand, a single diffractive optical element (DOE) can combine many continuous-wave lasers to kilowatt power levels [7–9]. Unfortunately, this combination technique does not work for ultrashort pulses, since a different pulse front tilt (PFT), or angular dispersion [10], introduced by the DOE for each input beam would cause significant combining loss. For example, when using this scheme to combine two 120 fs pulsed beams with a central wavelength at 1040 nm, even with a small diffraction angle of ∼10 mrad, the PFT introduced by the DOE for each beam is 33 fs/mm. Here the PFT angle reduces to the diffraction angle in small-angle conditions, which can be shown by relating the PFT to angular dispersion and applying the grating equation [10]. The two input beams acquire opposite PFTs; thus, even with a small beam size of ∼2 mm, the pulse delay mismatch upon combining can be as large as 66 fs, which results in inefficient combining of 120 fs pulses, either transform-limited or chirped.

Recently a novel coherent beam combination technique, which can combine a large number of ultrashort pulsed beams using a diffractive optic pair, was demonstrated [11,12]. The optic-pair combiner design cancels the PFT introduced by both diffractive optics for each input beam, leading to efficient combining, while minimizing uncorrected dispersion effects. One-dimensional combining of four ultrashort pulsed beams was demonstrated as the first proof of principle. However, for high-energy laser systems combining up to hundreds of beams, one-dimensional combination is impractical, due to system complexity, as well as large diffraction angles which would prevent efficient combination [11]. Thus, to move towards large-array high-energy systems, it is essential to develop a two-dimensional diffractive pulse combination, which can combine beams from a compact two-dimensional fiber array, while keeping small diffraction angles for optimal combining efficiency. In this Letter, we show experimentally that the diffractive pulse combination approach works in a scalable, two-dimensional array, by combining a square array of eight ultrashort pulse fiber apertures.

The concept of the two-dimensional diffractive combiner is illustrated in Fig. 1, where the combiner consists of two diffractive optical elements (DOEs), namely, DOE1 and DOE2. A square array of eight parallel ultrashort pulsed beams is incident on DOE1. DOE1 is essentially a 2-D array of blazed gratings, one for each input beam, directing all beams to one spot on DOE2. DOE2 is a 2-D, eight-way diffractive beam splitter operated in reverse, and there all beams from DOE1 are combined into a single output beam, providing that the pulse delays and phases are well matched. Both DOE1 and DOE2 are manufactured using a standard digitized surface-writing process, which is automated with digital design files and, thus, scalable.

For each input beam in Fig. 1, since the diffraction angle is small, the PFT angle introduced by DOE1 is the same as the

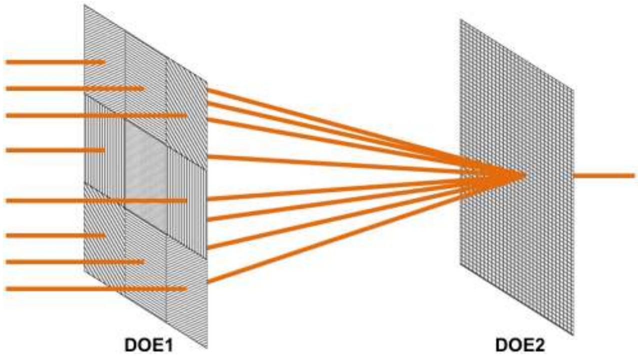

Fig. 1. Concept of the two-dimensional diffractive combiner.

diffraction angle. When each beam gets diffracted at DOE2, the reverse process occurs, and another opposite PFT is acquired. Since all input beams are parallel to each other and to the output beam, the diffractive optic pair exactly cancels the PFT, i.e., the output pulse front is parallel to the input pulse front for each beam, so that ultrashort pulses can be combined efficiently. The groove densities of both diffractive optics in the combiner are low, leading to small diffraction angles, as well as low temporal and spatial dispersions introduced by the DOE pair, resulting in negligible effects on combining efficiency, as we later describe quantitatively.

Since DOE2 in Fig. 1 is a diffractive beam splitter operated in reverse, for each beam diffracted from DOE1, DOE2 also acts as a 2-D eight-way beam splitter. Thus, when each diffracted beam is incident alone on DOE2, it produces a square eight-beam array, illustrated as an output subset in Fig. 2, i.e., input beam i produces output subset i after DOE2 ($i = 1, 2, \cdots, 8$). In output subset i, each of the eight split beams corresponds to a different diffraction angle off DOE2. As shown in Fig. 2, when all the input beams are present and combining is aligned, eight output subsets partially overlap with each other, forming a 5×5 output beam array. When the pulses in the input beams are delay-matched, but not phase-synchronized, all output subsets interfere with each other, and the beams in the 5×5 output array fluctuate in intensity. When the phases of the incident pulsed beams are synchronized, the output power is concentrated on the central beam of the 5×5 output array, i.e., all input beams are combined into a single output beam. Note that unwanted high-order diffractions of DOE2, accounting for up to a few percent of the total power in practical cases, are not considered in the description above. However, the high-order diffractions of all the beams incident on DOE2 interfere with each other, and with more intense low-order diffractions, thus decreasing the combining efficiency. Analysis considering high-order diffractions, as well as other detrimental effects due to manufacturing imperfections of DOE2, such as scattered light, is shown later in this Letter. Also note that there is no spatial chirp present on the output combined beam due to the symmetric arrangement of beams input to DOE2, where opposite spatial chirps are compensated for upon combining. By numerical simulation using VirtualLab software from LightTrans [11], it is shown that the output uncombined beams are spatially chirped, while the central combined beam has zero spatial chirp.

The experimental setup for two-dimensional pulsed beam combining is shown in Fig. 3. A pulse train is generated from a Yb-doped fiber mode-locked oscillator (Menlo Systems Orange), with a central wavelength at 1040 nm, a repetition rate of 100 MHz, and a transform-limited pulse width of 120 fs FWHM. The pulsed beam is coupled into a single-mode, polarization-maintaining (PM) fiber, split by a 50∶50 fiber splitter, and amplified by two single-mode PM Yb-doped fiber amplifiers (YDFAs) (Thorlabs YDFA100P), each with output power up to 150 mW. The amplified pulses are then split again using cascaded 50∶50 fiber splitters, into eight single-mode PM fiber channels, each with a phase modulator and a fiber collimator. Array-forming optics receives eight collimated beams from the fiber system and outputs a square array of eight parallel beams, incident on DOE1, the first element of the diffractive combiner. DOE1 diffracts all input beams towards one spot on DOE2, which is 2 m away from DOE1. The diffractive optic pair is custom manufactured by Holo/Or through a 16-level digitized surface-writing process. Both DOEs are transmissive and AR-coated for 1040 nm, and the groove densities are 6.8 and 4.8 lines/mm, corresponding to the outer and the inner input beams in the square array.

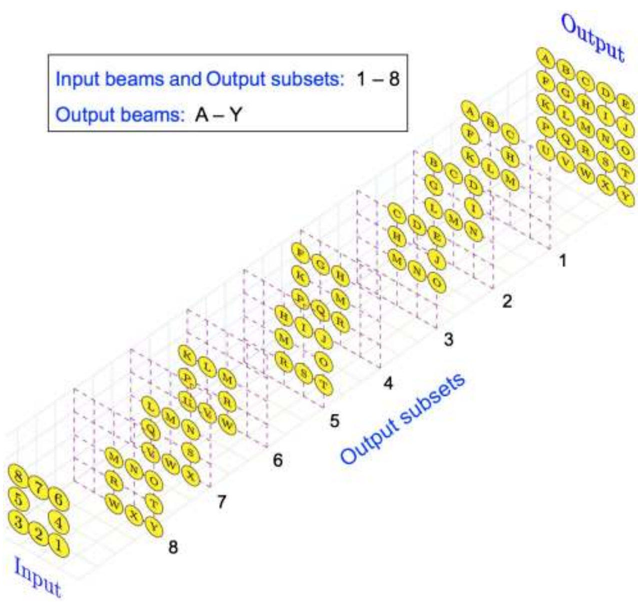

Fig. 2. Formation of the 5×5 uncombined beam array exiting DOE2, with a 3×3 incident beam array.

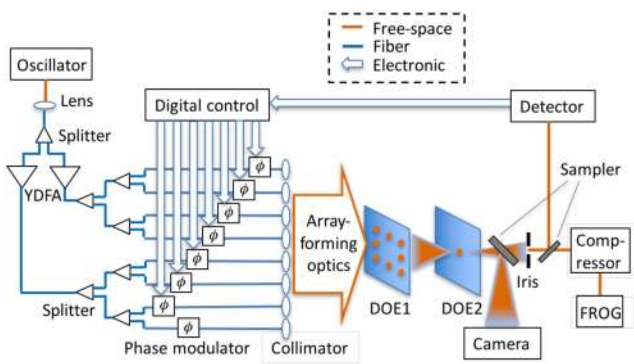

Fig. 3. Experimental setup. DOE1 and DOE2 are separated by 2 m; the camera is 2 m away from DOE2.

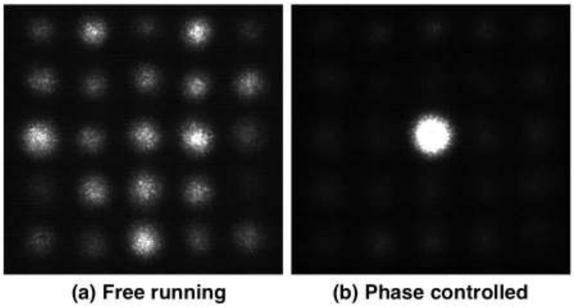

Fig. 4. Sampled combiner output beam array from a CCD camera.

Waveplates and polarizers are incorporated before DOE1 to guarantee the same polarization and power for the input beams. The input beam array has an adjacent beam separation of 10 mm, with a beam size of 2.7 mm.

The output beam array from DOE2, which is sampled by a CCD camera, is a 5 × 5 array of beams fluctuating in intensity as the relative phases change when the system is free-running, shown in Fig. 4(a), and becomes one combined central beam when the system is phase controlled, shown in Fig. 4(b). Here high-order diffracted output beams outside the 5 × 5 array, whose power is a few percent of the total, are not included in Fig. 4. The central output beam is launched into a grating compressor, compensating for the group delay dispersion of the combined pulse [13]. A FROG from Swamp Optics diagnoses the combined and compressed pulse. Pulse delays of all input beams need to be matched within a few micrometers for efficient combination of 120 fs pulses. This is achieved by adjusting the fiber collimators mounted on precision translation stages, based on maximizing observed interferences. Optical phases of the input beams are synchronized by monitoring the power of the combined central beam with a sampler and a photodiode, applying a stochastic parallel gradient descent algorithm, which keeps making fast parallel phase dithers and subsequent phase corrections to maximize the sampled signal [14]. Both phase dithers and corrections are applied to the phase modulators in the fiber channels.

Pulse width and shape preservation are critical requirements of coherent pulse combining. To check this, one of the input pulses to the diffractive optic pair is launched into the grating compressor with optimized pulse compression, and then diagnosed by FROG. This diagnosed compressed input pulse is compared with the output combined and compressed pulse when the system is phase controlled, as shown in Fig. 5. Note that the pulses in all input beams to DOE1 are identical, since they propagate through identical optical components from the mode-locked oscillator to DOE1, i.e., they experience the same dispersion and nonlinearity. From Fig. 5, the combined and compressed pulse preserves the input pulse shape and the 120 fs transform-limited pulse width. Slight broadening of the combined pulse is believed to result from imperfect delay matching of the input pulses.

By integrating beam intensities of the sampled combiner output from the CCD camera, the combining efficiency, defined as the ratio of the central combined beam power to the total output power of the diffractive combiner, is measured to be 89.5%, when the input pulse phase synchronization is optimized. The overall efficiency, defined as the ratio of the central combined beam power to the total input power of DOE1, is measured to be 85.4%, taking into account the diffraction efficiency of DOE1 and the transmissivity of DOE2.

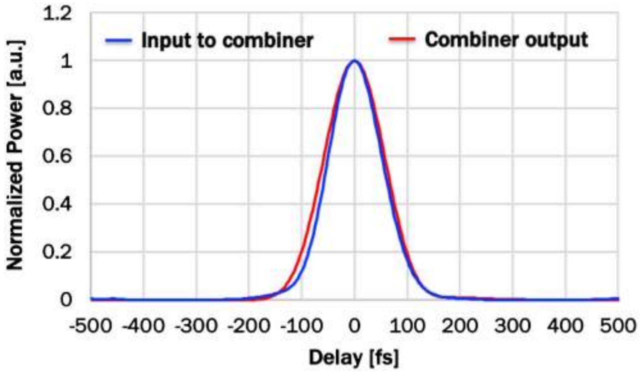

Fig. 5. Input and output pulses of the diffractive optic pair, compressed and diagnosed by a FROG.

We can analyze the factors causing combining efficiency loss quantitatively. The effects of mismatched temporal and spatial dispersions, introduced by the diffractive combiner, can be evaluated using the analytic theory of dispersion effects on combining efficiency [11]. Maximum group delay introduced by the diffractive optic pair, corresponding to the corner beams in the square input array, is calculated to be 4 fs for the experiment in this Letter, or 1/30 of the pulse width, using

$$\mathrm{GD} \approx \frac{r\theta}{c}\frac{\Delta\lambda}{\lambda_0}, \tag{1}$$

where r is the distance between the input beam and the central axis, θ is the diffraction angle, c is the speed of light, and $\Delta\lambda/\lambda_0$ is the fractional bandwidth of the ultrashort pulse. More precisely, the combining efficiency loss due to mismatched group delay dispersion is calculated to be 0.0015%, by applying

$$\Delta\eta_T = \frac{3\ln^2 2}{4}\left(\frac{\lambda_0 l^2}{\pi c^2 \tau_p^2 L}\right)^2 \sigma_{Nr}^2, \tag{2}$$

where λ_0 is the pulse central wavelength, l is the input beam separation, τ_p is the power FWHM pulse width, L is the separation of the diffractive optic pair, and σ_{Nr}^2 is the variance coefficient [11], 0.25 for a 3 × 3 beam array. Maximum beam displacement due to spatial dispersion, corresponding to the corner beams in the square input array, is calculated to be 0.17 mm using

$$\Delta h \approx r\frac{\Delta\lambda}{\lambda_0}, \tag{3}$$

while the beam size is 2.7 mm. More accurately, the combining efficiency loss due to mismatched spatial dispersion is calculated to be 0.24% with

$$\Delta\eta_s = \frac{\ln 2}{3\pi^2}(N^2 - 1)\left(\frac{l\lambda_0}{D\tau_p c}\right)^2, \tag{4}$$

where D is the beam diameter and N is the input beam array size, 3, for the experiment in this Letter. Thus, mismatched temporal and spatial dispersions have negligible effects on the combining experiment in this Letter. It has been calculated that this combining scheme can be scaled to ~200 beams with

130 fs pulses, which is currently being planned, with only a few percent additional combining loss due to temporal and spatial dispersions [11]. From Eqs. (2) and (4), shorter pulse durations will cause more combining loss, but it is compensable by adjusting spatial arrangements, such as the DOE separation and the input beam separation. Thus, this combining technique can support short pulse durations well below 100 fs with variations of system parameters.

The effects due to manufacturing imperfections of DOE2, such as high-order diffractions and scattered light, establish a practical limit of achievable combining efficiency. Since the experimental DOE2 was manufactured using a standard digitized surface-writing process, the finite number of bits used in the process, as well as a discontinuous surface profile with resetting steps every 2π of phase, result in departure from optimal performance. When DOE2 is used as a 1-to-8 beam splitter (the reverse process of beam combining), the intrinsic efficiency of DOE2 can be expressed as

$$\eta_I = \sum_{n=1}^{8} D_n^2, \tag{5}$$

where D_n^2 is the power splitting fraction in the nth output channel [15]. Here only the splitting channels with $n = 1, 2, \ldots, 8$ are of interest for beam combining. When the 1-to-8 beam splitter is used in reverse for beam combining, the highest combining efficiency reduces to η_I, in the absence of other detrimental effects, when the relative input powers are matched to the splitting fractions [16]. The intrinsic efficiency of the experimental DOE2 is measured to be 90.7% with a power meter. Since the measured combining efficiency is 89.5%, close to the DOE2 intrinsic efficiency, we believe that system mismatches, such as nonuniform input power and polarization, pulse delay mismatch, uncompensated temporal and spatial dispersions, and spatial beam misalignments, have minimal effects on beam combination.

To conclude, a two-dimensional diffractive beam combination for ultrashort pulses is demonstrated for the first time, to the best of our knowledge, showing the potential of using a diffractive optic pair to combine a large number of ultrashort pulsed beams. A square array of chirped pulse beams from eight parallel fiber channels is coherently combined into one beam, and the combined pulse is compressed back to the 120 fs transform-limited pulse width. Combining efficiency is optimized by eliminating system mismatches, approaching the limit due to manufacturing imperfections of the diffractive optic. Uncompensated temporal and spatial dispersions are calculated to have minimal effects on combining. In future work, to achieve higher combining efficiencies, DOE intrinsic efficiencies can be improved by increasing the number of bits used in the digitized surface-writing manufacture process and, further, by incorporating continuous surface-relief phase gratings [7,17]. Towards higher scalability, current free-space array-forming optics and individual collimators can be replaced by precision fiber bundles and common collimating lenses. It has been calculated that this combining scheme can be scaled to ∼200 beams with small additional combining loss due to temporal and spatial dispersions [11]. It is expected that this diffractive pulse combination technique can be applied to high-power, large-array, high-efficiency fiber laser combination systems.

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