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High Power Coherent Beam Combining Setup Using Modified Cascaded Multi-dithering Technique

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A modified setup of a CMD technique for high power coherent beam combining was presented to address an issue of low damage threshold of electro-optic modulators. The feasibility of the modified setup was demonstrated by combining eight fiber beams, and it was successfully performed with λ/44 of residual phase error and 100 Hz of control bandwidth. It is expected that the modified CMD setup facilitates ultra-high power coherent beam combination without a limitation caused by the low damage threshold of electro-optic modulators.

Keywords : High power laser, Phase extraction
OCIS codes : (060.5060) Phase modulation; (140.3298) Laser beam combining

I. INTRODUCTION

Coherent beam combining is a method used to achieve high power by coherently adding lower power beam elements. It has been highlighted as an alternative way to scale up the power of high power lasers, which face problems with thermal and nonlinear effects [1]. To combine a large number of beam elements to obtain maximum output power, it is necessary to use active phase locking, which simultaneously measures and locks the phases of the beam elements. There are three main methods of active phase locking: heterodyne detection [2-4], the stochastic parallel gradient descent (SPGD) algorithm [5-7], and a multi-dithering technique known as the locking of optical coherence by single detector electronic-frequency tagging (LOCSET) technique [8-11]. Among these methods, the LOCSET technique controls the phases of beam elements by modulating the phases with different frequencies and demodulating the signal of the combined beam with the applied frequencies. It has shown excellent performance in terms of phase stability and the number of beam elements that can be combined with only one detector. Nevertheless, the maximum number of beam elements that can be combined when combining high-power amplified beam element using LOCSET is limited to between 100 and 200, because the number of modulating frequencies is limited 100 to 200, due to the constraint of the control bandwidth of the phase locking system [12].

In 2015, the Cascaded Multi-Dithering (CMD) technique was first proposed to solve this limitation, by modulating beam elements in series and combining them as a form of array. Unlike the original LOCSET technique, the number of modulating frequencies is not limited in the CMD technique. This was successfully demonstrated by combining sixteen beam elements at that time [13]. Furthermore, the feasibility of the CMD technique as a method of combining a substantial number of beam elements was verified by equations and analytical simulations in 2016 [14].

However, the CMD technique is still not sufficient to combine high-power amplified beam elements, because of the low damage threshold of the electro-optic modulator, such as LiNbO3, which dithers the high power beam elements after amplification. The damage threshold of typical electro-optic modulators is at about the sub-Watt level [15],

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which is lower than typical pre-amplified power.

In this paper, a modified setup of the CMD technique is presented for high power laser beam combination. By simply changing the configuration of the CMD technique, the problem of the low damage threshold of phase modulators is easily solved, enhancing the capability of the CMD technique as a powerful tool for combining a multiplexed number of high power amplified beam elements.

II. METHODS

A schematic diagram of an M by N beam combination using the CMD technique is illustrated in Fig. 1 [13]. It was verified by combining 4 by 4 (=16) beam elements. In practice, however, as the number of beam elements N in the 1st line increases, the power of the beam elements in the 2nd line arrays combined in the 1st line arrays increases as well, so the power easily exceeds the damage threshold of the phase modulators in the 2nd line. Therefore, another concept for the CMD technique is needed.

The problem can be overcome by putting the phase modulators in the 2nd line before the 1st line starts. The modified setup for the CMD technique is depicted in Fig. 2.

The modified concept consists of three parts: the 1st part is to modulate the beam elements in the 1st line, the 2nd part is to modulate beam elements in the 2nd line and to lock the phases of the beam elements in the 2nd line, and the last part is to lock the phases of the beam elements which are the combined beams of the 2nd line. Then all of the amplifiers are put behind the modulators so that the low damage threshold of the modulators is not a problem anymore.

The concept of changing the position of all phase modulators to in front of the amplifiers was introduced in a book [16] and has been applied to other articles dealing with coherent beam combining [6]. However, unlike other experiments, in order to apply the concept to the CMD technique, it should be considered additionally that the harmonic frequencies from modulating terms of the 1st line and the 2nd line have no influence on each LOCSET feedback. Compared with the setup in the Fig. 1 that the final feedback system in the 2nd line locks the phases of the beam elements which were already stable through phase locking in the 1st line, each feedback system in the 2nd part in Fig. 2 should lock the phases of beam elements which not only include double modulating frequencies but also were not phase-locked before. Therefore, if unwanted harmonic frequencies appear, the setup in Fig. 2 would be more vulnerable than the setup in Fig. 1.

The feasibility of the setup in the Fig. 2 is proved by developing equations first. In the setup, the electric field of the kth modulated beam E_k, one of the M beams in the 1st line is,

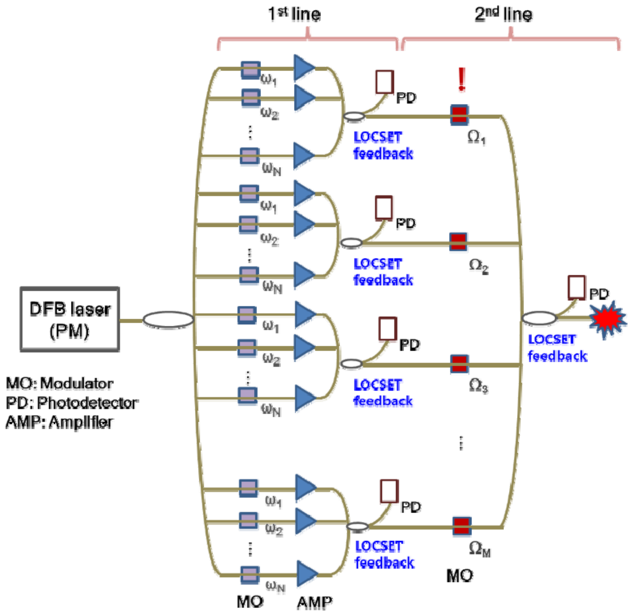

FIG. 1. A schematic diagram of an N by M beam combination using the CMD technique.

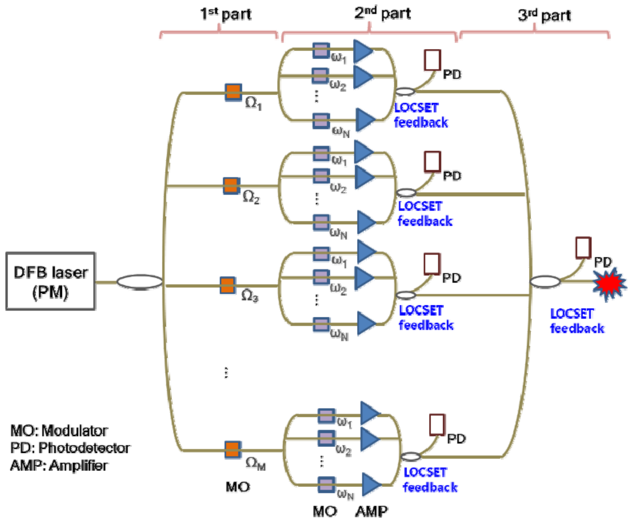

FIG. 2. The modified schematic diagram of an N by M beam combination using the proposed CMD technique.

$$E_k(t) = E_0 \cdot \cos(\omega_L t + \gamma_k \sin(\Omega_k t)), \tag{1}$$

where E_0 and ω_L represent the field amplitude for the kth modulated beam and laser frequency, respectively. Ω_k and γ_k represent the modulating frequency and the modulating depth for the kth modulated beam, respectively.

Then the kth beam is divided into N beam elements in the 2nd line. Among the N beams, the ith beam element of the 2nd line is modulated by ω_i and boosted by amplifier,

$$E_{ki}(t) = E_0 \cdot \cos(\omega_L t + \gamma_k \sin(\Omega_k t) + \beta_i \sin(\omega_i t) + \phi_i), \tag{2}$$

where ω_i and β_i represent the modulating frequency and the modulating depth for the i^th^ modulated beam, respectively. ϕ_i represents the optical phase for the ith modulated beam perturbed by the ith amplifier.

Afterwards, the N beam elements are combined into one beam, which is the ith beam element in the 1st line again,

$$E_k = \sum_{i=1}^{N} E_0 \cdot \cos(\omega_L t + \gamma_k \sin(\Omega_k t) + \beta_i \sin(\omega_i t) + \phi_i). \quad (3)$$

This is the same as the kth modulated beam in the 2nd line in the original schematic diagram (Fig. 1) [13].

The photocurrent i_{PD} detected at the photodetectors in the 2nd part can be expressed as an interference signal between N modulated beams:

$$\begin{aligned} i_{PD} = R_{PD} \cdot A \cdot \sqrt{\frac{\mu_0}{\epsilon_0}} &\cdot \left(\sum_{i=1}^{N} E_0 \cdot \cos(\omega_L t + \gamma_k \sin(\Omega_k t) + \beta_i \sin(\omega_i t) + \phi_i) \right) \\ &\cdot \left(\sum_{j=1}^{N} E_0 \cdot \cos(\omega_L t + \gamma_k \sin(\Omega_k t) + \beta_j \sin(\omega_j t) + \phi_j) \right). \end{aligned} \quad (4)$$

Here, i and j represent the summation indices of each modulated beam. μ_0 and ε_0 represent the magnetic and electric permeabilities of free space, respectively, and R_{PD} and A represent the responsivity and the active area of the photodetector, respectively. E_0' represents the amplitude for the amplified electric field.

Then, the ith phase error signal S_i is developed below.

$$\begin{aligned} S_i &= \frac{1}{\tau} \int_0^{\tau} i_{PD}(t) \cdot \sin(\omega_i t) dt \\ &= \frac{E_0^2}{2} J_1(\beta_i) J_0(\beta_j) J_0(\gamma_k) J_0(\gamma_l) N \phi_i \end{aligned} \quad (5)$$

Therefore, we can lock the phase of the ith beam by giving feedback signals proportional to the ith phase.

Using the above locking process, we can obtain the M combined beams which become the M beam elements of the last part. They are perturbed again after passing through amplifiers in the last part and then re-combined into one beam. Finally, the electric field of the last combined beam is described below,

$$E_k = \sum_{k=1}^{M} \sqrt{N} E_0 \cdot \cos(\omega_L t + \gamma_k \sin(\Omega_k t) + \beta_i \sin(\omega_i t) + \Phi_k), \quad (6)$$

which has the same form as Eq. (3). Following the above procedure, the kth phase error signal S_k is developed below.

$$\begin{aligned} S_i &= \frac{1}{\tau} \int_0^{\tau} i_{PD}(t) \cdot \sin(\Omega_k t) dt \\ &= \frac{E_0^2}{2} J_0(\beta_i) J_0(\beta_j) J_1(\gamma_k) J_0(\gamma_l) M \Phi_k \end{aligned} \quad (7)$$

The only difference between Eq. (5) and Eq. (7) is the demodulating frequencies ω_i and Ω_k.

Furthermore, the point that there is no coupling effect between the frequencies of each part was proved by earlier experiments [13, 14].

As a consequence, we conclude that the locking process of the modified setup (Fig. 2) is as feasible as that in the original setup (Fig. 1).

III. RESULTS AND DISCUSSION

To verify the feasibility of the modified scheme, we demonstrated it by combining eight fiber beam elements. The experimental setup of the scheme is illustrated in Fig. 3.

A beam coming from a polarization maintaining DFB laser is split into two beam elements. Afterwards, the two beam elements are modulated with different modulating frequencies Ω1, Ω2 and split into four beam elements. The four beam elements of each array are modulated with different frequencies ω1 to ω4 and then re-combined into one beam through LOCSET. Lastly, the two combined beams are combined into one beam through LOCSET as well.

To create a realistic circumstance, we made amplifier-like noises and applied them to the beam elements. The given noises were created with reference to the noises measured at 10 W [17]. Here, PZT tubes were employed as phase modulators and noise generators and the same modulating frequencies applied in the original setup were used in order to produce the same conditions as the original setup and to allow the comparison.

As a result, the eight beam elements were successfully combined, as shown in Fig. 4. It shows that the normalized intensity of the combined beam fluctuates between 0 and 1 without any control in the open loop whereas it is close to 1 in the closed loop. In this case, the residual recorded phase error was λ/44, which satisfies the phase matching tolerance of λ/20 [18].

In addition, we calculated the power spectral density of the phase of the combined beam in order to obtain the control bandwidth of the modified CMD setup. The result is depicted in Fig. 5.

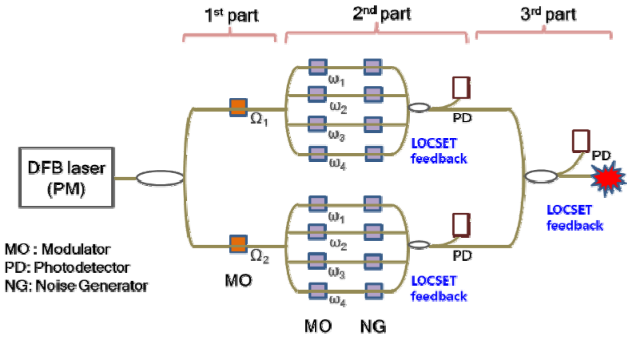

FIG. 3. Experimental setup of the modified scheme.

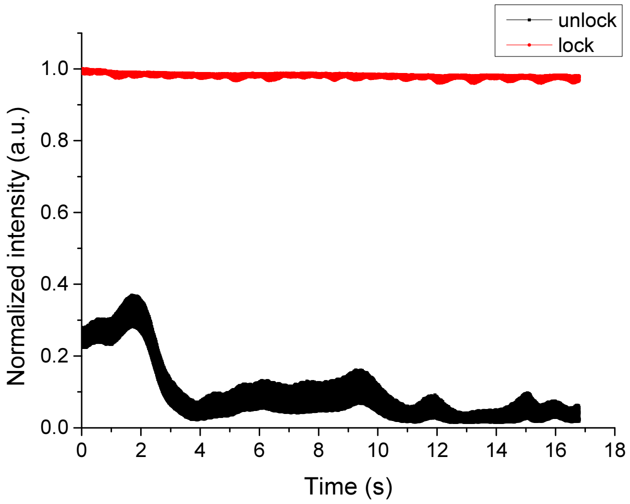

FIG. 4. Normalized intensity of the combined beam in the open loop (black) and in the closed loop (red).

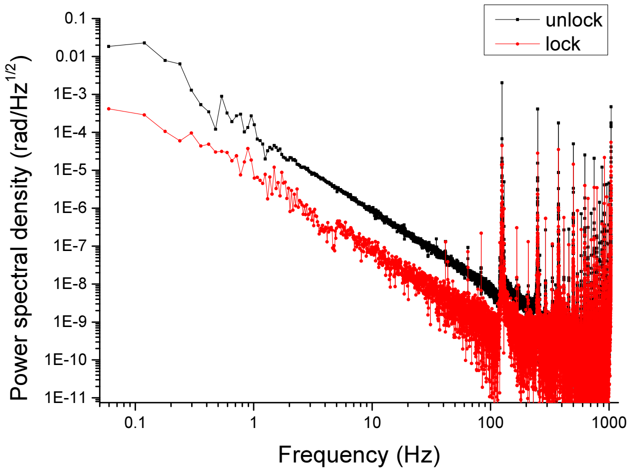

FIG. 5. Power spectral density of the phase of the combined beam in the modified CMD setup.

In Fig. 5, the power spectral density of the combined beam with locking is far lower than that of the combined beam without locking in the range below 100 Hz. It shows that the control bandwidth of the modified scheme is higher than 100 Hz, which result is comparable with that of the original setup [19]. If voltage amplifiers were applied in each phase modulator, a higher control bandwidth would be possible, so additional amplifiers could be added at the end of the 2nd part.

IV. CONCLUSION

In summary, a modified setup of the CMD technique for high power coherent beam combining was proposed and demonstrated with an eight fiber beam combination. It was successfully performed with λ/44 of residual phase error and 100 Hz of control bandwidth. Using the modified CMD setup, we can expect to combine high power amplified-beam elements using the CMD technique, without the limiting constraint of the damage threshold of the modulators.

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