Cascaded multi-dithering theory for coherent beam combining of multiplexed beam elements

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Abstract: The Cascaded Multi-Dithering theory, which allows coherent beam combining of M-by-N beam elements, is presented in this paper. The theory of Cascaded Multi-Dithering is briefly introduced, and demonstrated experimentally by combining sixteen-beams to verify its feasibility as an active phase control for scaling up the power of fiber lasers.

OCIS codes: (140.3298) Laser beam combining; (060.5060) Phase modulation.

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1. Introduction

The output power of fiber lasers has been continuously increased to meet the demand for high power and high brightness laser sources. In 2014, IPG reported achieving a 20 kW output in a nearly diffraction-limited beam [1]. However, scaling up the output power from a single fiber laser introduces challenging problems, such as thermal damage and nonlinear effects, which limit the output power to several tens of kilowatts [2,3]. Therefore, researchers have given more attention to coherent beam combination (CBC) approach, which provides high power and high beam quality simply by combining multiple beam elements, without scaling up the power of any single beam element [4].

The most critical requirement to achieve CBC is to lock the phases of the beam elements to be combined, using passive or active methods. Passive phase locking makes it simple to add the beam elements, but is not suitable for scaling up output power [5]. Active phase locking, which measures phase differences between the beam elements and locks the phases by giving feedback voltages to the beam elements in real time, has been employed for combining many beams. There are several representative methods in active phase locking for scaling up the number of beams: the stochastic parallel gradient descent (SPGD) algorithm [6–8], multi-dithering technique [9–11], and single frequency dithering technique [12,13].

In SPGD, small perturbations are given to each beam element through phase modulators in the form of voltages and the perturbations are updated to maximize the intensity of a combined beam through iteration. 4 kW output power was recorded by combining eight beam elements in 2011 [7], and 1.14 kW output power of was obtained by combining nine beam elements in the same year [8]. Nevertheless, the ability to scale up the number of beam elements is limited in SPGD, because the control bandwidth is decreased with the increasing number of beam elements [14].

In multi-dithering techniques, such as the locking of optical coherence by single-detector electronic-frequency tagging (LOCSET) method, all beam elements are dithered at different frequencies by modulators, and phase differences are obtained from the interference signal of a combined beam, and the phases of the beam elements are locked by applying feedback voltages through the modulators. A kW class output power was obtained by combining five beam elements in 2009 [9] and sixteen beam elements were recorded as the largest number of beam elements to be combined through LOCSET methods in 2011 [14]. However, the total number of combined beam elements in the LOCSET technique is restricted to between 100 and 200 as the maximum number of modulating frequencies is limited [10].

The single frequency dithering technique is like time division multiple analysis (TDMA) in telecommunications, whereas LOCSET corresponds to frequency division multiple analysis (FDMA). Therefore, the single frequency dithering technique encounters a problem similar to LOCSET, not in the frequency domain, but in the time domain.

Summing up, the number of beam elements in CBC is limited to up to 200 in all of the active phase locking methods so far.

In this paper, we propose a Cascaded Multi-Dithering (CMD) technique as the solution to the above problem, by removing the limitation of the total number of beam elements to be combined. In the technique, firstly, N beam elements are modulated at different frequencies and combined. Secondly, M beam elements, each of which is a combination of N beam elements, are modulated again at frequencies different from the previously used ones and re-combined. With such procedures, each of the M systems, comprised of the N beam elements, can be modulated at the same set of different frequencies, which makes it possible to combine a substantial number of beams.

The paper is ordered as follow. First, we describe the theory of LOCSET to explain the basic principle of the multi-dithering technique and expand it to CMD theory. Afterwards, we demonstrate the CMD technique by combining sixteen beam elements, to prove the feasibility of the CMD theory.

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2. Theory

The experimental scheme of the cascaded LOCSET is shown in Fig. 1. The first line phase locking consists of M phase locking systems, each of which combines N beam elements through LOCSET.

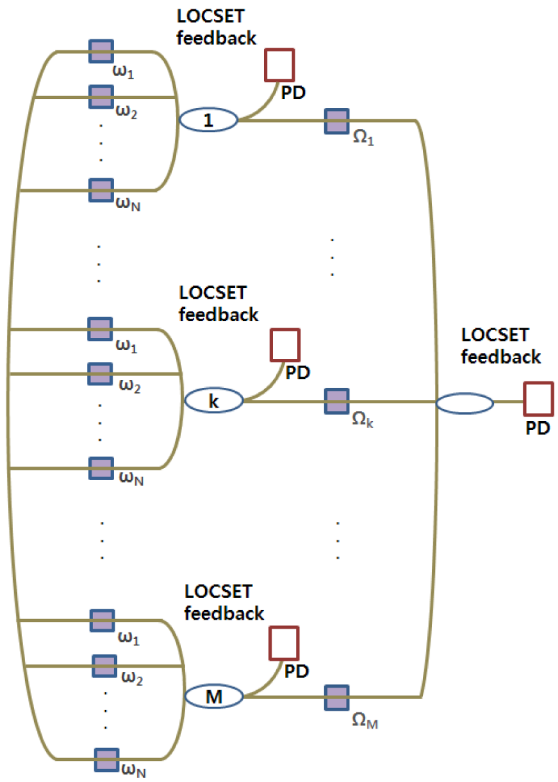

Fig. 1. Schematic diagram of cascaded multi-dithering

Assuming self-synchronous LOCSET [15], the electric field of the i^{th} modulated beam E_i, one of the N beams in the single phase locking system is,

$$E_i(t) = E_{i0} \cdot \cos(\omega_L t + \phi_i + \beta_i \sin(\omega_i t)), \tag{1}$$

where E_{i0} represents the field amplitude for the i^{th} modulated beam and ω_i and β_i represent the modulating frequency and the modulating depth for the i^{th} modulated beam, respectively. ω_L and ϕ_i represent laser frequency and optical phase of i^{th} beam, respectively.

Substituting the trigonometric identity for the cosine of the sum of the optical phase and the phase modulating term into Eq. (1),

$$E_i(t) = E_{i0} \cdot \begin{bmatrix} \cos(\omega_L t + \phi_i)\cos(\beta_i \sin(\omega_i t)) \\ -\sin(\omega_L t + \phi_i)\sin(\beta_i \sin(\omega_i t)) \end{bmatrix}. \tag{2}$$

The photocurrent i_{PD} detected at the photodiode is expressed as an interference signal between modulated beams:

$$i_{PD} = R_{PD} \cdot A \cdot \sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \left(\sum_{i=1}^{N} E_i(t) \right) \left(\sum_{j=1}^{N} E_j(t) \right), \tag{3}$$

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where N represents the number of modulated beams and 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.

Skipping the complex calculation, we focus on getting the c^{th} phase signal for phase locking. The c^{th} phase error signal S_c that we are interested in can be obtained by demodulating the photocurrent i_{PD} for the c^{th} modulating frequency ω_c, yielding:

$$S_c = \frac{1}{\tau}\int_0^{\tau} i_{PD}(t)\cdot\sin(\omega_c t)\,\mathrm{dt} \quad , \tag{4}$$

In the original LOCSET theory, when $\omega_i = \omega_c$ it is required that integration time τ should be far longer than $2\pi/\omega_i$ and $\tau \gg 2\pi/|\omega_i-\omega_j|$ for all i and j when $j\neq i$, so that the Eq. (4) fulfills the sine and cosine orthogonalities and is approximated as a simple expression. This expression is then:

$$S_i = R_{PD}\cdot\sqrt{P_i}\cdot J_1(\beta_i)\cdot\sum_{j=1}^{N}\sqrt{P_j}\cdot J_0(\beta_j)\cdot\sin(\phi_j-\phi_i) \quad , \tag{5}$$

where ϕ_j and ϕ_i represent the phases of the j^{th} and i^{th} phase modulated beam, respectively. P_i represents the optical power of the i^{th} modulated beam:

$$P_i = \frac{A\cdot E_{i0}^2}{2}\sqrt{\frac{\mu_0}{\varepsilon_0}}. \tag{6}$$

When each of M systems in the 1st line is phase-locked and the combined beams are optimized, all combined beam from 1 to M go to the 2nd line, and are phase-modulated again at a set of frequencies Ω_1, …, Ω_M, respectively. The electric field of the k^{th} modulated beam E_k among M beams is,

$$E_k = \sum_{i=1}^{N} E_0\cdot\cos(\omega_L\,\mathrm{t} + \Phi_k + \beta_i\sin(\omega_i\,\mathrm{t}) + \gamma_k\sin(\Omega_k\,\mathrm{t})), \tag{7}$$

where γ_k and Φ_k represent the modulating depth and the optical phase for the k^{th} modulated beam, respectively.

$$S_k = \int_0^{T} i_{PD}\cdot\sin(\Omega_k\,\mathrm{t})\,\mathrm{dt} = \frac{E_0^2}{2}\mathrm{J}_0(\beta_j)\mathrm{J}_0(\gamma_l)\mathrm{J}_0(\beta_i)\mathrm{J}_1(\gamma_k)\mathrm{N}^2\sum_{l=1}^{M}\sin(\Phi_k-\Phi_l) \quad . \tag{8}$$

Assuming that Φ_k-Φ_l is small enough to be neglected after several feedbacks, $\sin(\Phi_k$-$\Phi_l)$ can be approximated as Φ_k-Φ_l and the phase error signal S_k is,

$$= \frac{E_0^2}{2}\mathrm{J}_0(\beta_j)\mathrm{J}_0(\gamma_l)\mathrm{J}_0(\beta_i)\mathrm{J}_1(\gamma_k)\mathrm{N}^2\sum_{l=1}^{M}(\Phi_k-\Phi_l). \tag{9}$$

In Eq. (9), it is evident that the response of the k^{th} control signal due to a disturbance in the phase of the k^{th} element is M times stronger than the response of the k^{th} control signal due to an equal magnitude disturbance in one of the other beam elements, since in Eq. (9) the second term in summation corresponds to a weighted ensemble average of the phase fluctuations in the beam elements, which reduces the influence of the fluctuations of other beam elements on the stability of the k^{th} beam elements phase, whereas the first term in the summation increases the control loop signal for fluctuations in the element being controlled, the k^{th} beam element. Therefore, as M increases, this decreases the influence of fluctuation in the other beam

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elements on the k^{th} beam element while increasing the error signal strength [15]. As a consequence, S is approximated as,

$$S_k = \frac{E_0^2}{2} \mathrm{J}_0(\beta_j)\mathrm{J}_0(\gamma_l)\mathrm{J}_0(\beta_i)\mathrm{J}_1(\gamma_k)\mathrm{N}^2 \cdot (\mathrm{M}\,\Phi_k) \tag{10}$$

From Eq. (10), we can calculate the phase error of the k^{th} beam Φ_k through the k^{th} phase error signal S_k and lock the phase of each beam by giving feedback signals proportional to the phase differences of each beam element to it.

In the beam combination using the LOCSET method, the total number of beam elements N is limited. This is because the modulating frequencies $\omega_1, \ldots, \omega_N$, dithering with modulators whose bandwidths are fixed to several hundred MHz, have to be different from each other while maintaining about several hundred kHz of control bandwidth, to control high-frequency noises caused by high power amplifiers. However, in the case of CMD, N beam elements are combined into one beam through LOCSET, and the combined beams form an array. Each of M combined beams can be re-combined through LOCSET as well after being modulated at a series of frequencies $\Omega_1, \ldots, \Omega_M$ that are different from the previous ones. As a consequence, M arrays of N beam elements which have the same set of modulating frequencies $\omega_1, \ldots, \omega_N$ can theoretically be re-combined to without the limitation of the total number of N.

Of course, there are still constraints on choosing ω_1 to ω_N and $\Omega_1, \ldots, \Omega_M$ in CMD. First of all, the modulating frequencies to be used in the 1st line and 2nd line should be chosen in the range of 0 to several hundred MHz, the same condition as in LOCSET. Second, they should have more than a MHz of frequency difference between one another so as to be discriminated from one another, while maintaining the same control bandwidth as that of LOCSET. Therefore, if we simply determine the 2nd line modulating frequencies $\Omega_1, \ldots, \Omega_M$ among ω_1 to ω_N of original LOCSET, the number of the 1st line modulating frequencies N is reduced to M-N to satisfy the above two requirements. For example, if M is determined to be N/2 in CMD, the number of modulating frequencies which can be employed in the 1st line is reduced to N/2, (ω_1, $\omega_{3,\ldots,}$ $\omega_{2N-1,\ldots,}$ ω_N), then the 2nd line modulating frequencies $\Omega_1, \ldots, \Omega_{M(=N/2)}$ can be chosen as ω_2, $\omega_{4,\ldots,}$ $\omega_{2N,\ldots,}$ ω_{N-1}. Consequently, the total number of beam elements to be combined in a two dimensional CMD with the same control bandwidth as original LOCSET extends up to N/2 by N/2 = $N^2/4$, the maximum number in this two dimensional case. As mentioned above, if N = 200, then the maximum number of beam elements to be combined is $(200)^2/4$ = 10,000. Furthermore, it can be expanded to be not only two dimensional, but also to be multidimensional, which facilitates a massive-scale coherent beam combining.

3. Experimental setup and results

To show the feasibility of cascaded multi-dithering, we performed a 16 beam combination with four-by-four arrays. The experimental setup is depicted in Fig. 2. A beam coming from a 1,550 nm polarization maintaining (PM) distributed feedback (DFB) fiber laser with a maximum output power of 1 W, is divided into 16 beam elements passing through a one-by-sixteen beam splitter (also a PM component). The sixteen beam elements then form four arrays of the 1st line, and the four beam elements of an array are modulated at the same series of frequencies $\omega_1, \ldots, \omega_4$ with PZT tubes as modulators [16,17], and are combined into one beam. The values of $\omega_1, \ldots, \omega_4$ are 8,333 Hz, 6,250 Hz, 4,167 Hz, and 2,083 Hz, respectively. A small portion of each combined beam is then sampled and goes to a photodiode in order to lock the phases of the four beam elements in each array. At the same time, a large portion of each combined beam forms an array of the 2nd line, whose beam elements are modulated with PZT tubes at frequencies $\Omega_1, \ldots, \Omega_4$. The values of $\Omega_1, \ldots, \Omega_4$ are 6,666 Hz, 5,000 Hz, 3,333 Hz, and 1,667 Hz, respectively, which are different from the previous ones.

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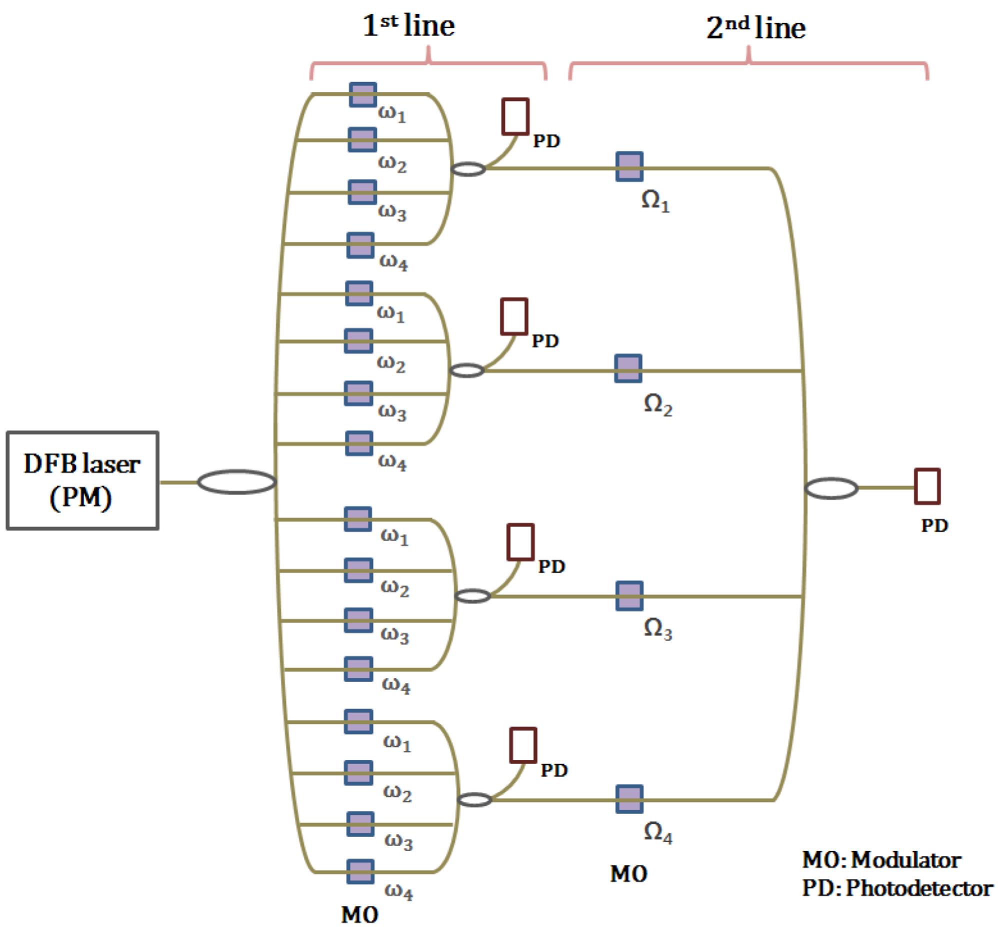

Fig. 2. Experimental setup of 16-beam combination through cascaded multi-dithering

Finally, all beam elements are combined into one beam whose phases are locked through LOCSET as well. All of the LOCSET electronics consist of data acquisition (DAQ) boards, analog input and output boards. In order to achieve the highest control bandwidth from the PZT tubes, used in the low frequency range up to 30 kHz [16], a modified-LOCSET technique was used in this experiment [17].

As a consequence, the result is shown in Fig. 3. It can be seen that the intensity of the combined beam randomly fluctuates zero to one in the open loop (blue) whereas it is optimized and is closed to one after phase locking starts in the closed loop. The residual phase error calculated through equations in [18], was recorded as λ/31, which satisfies the phase matching tolerance of λ/20 [19].

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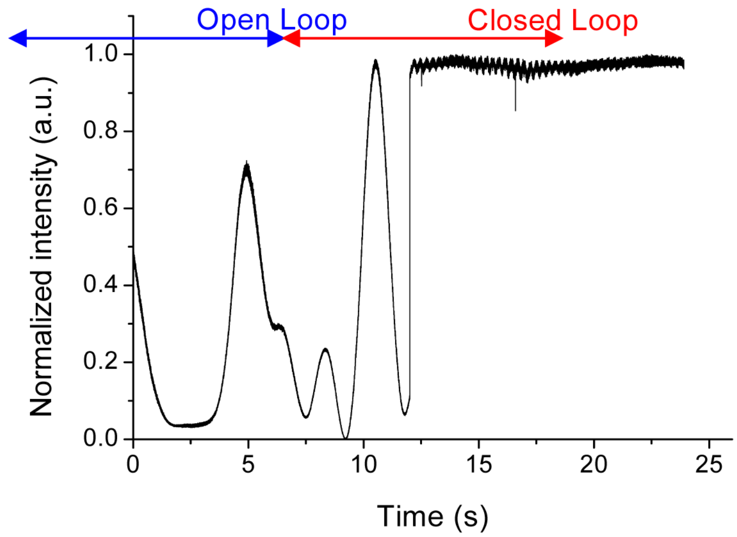

Fig. 3. Intensity signals of the combined beam in the open loop and the close loop in time domain

4. Conclusions

In summary, the CMD technique for coherently combining an unlimited number of beam elements has been suggested and demonstrated experimentally by combining 16 beam elements with PZT tubes as modulators. To prove the performance of this system, the phase stability of the combined beam was measured and the residual phase of $\lambda/31$ was obtained. From this result, we expect that a high power laser sources using coherent beam combination will establish a remarkable improvement in terms of power scalability through the application of the CMD technique.

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