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An active phase locking of multiple fiber channels via square wave dithering algorithm

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ABSTRACT

A novel active phase locking technique base on single detector is proposed and demonstrated experimentally. Using dual-level rectangular-wave phase modulation and time division multiplexing, the proposed multi-level phase dithering technique can achieve the same phase error signal as single/multi-frequency dithering technique, but without coherent demodulation circuit. Experimental investigation on coherent beam combination of 10 fiber laser beams is successfully demonstrated, with imposing an additional phase disturbances to mimic the phase noises in the high power fiber amplifiers. The combining efficiency with modulated phase noise is achieved above 97.55% and the accuracy of phase control is improved to $\lambda/42$ rms. One of the application fields, i.e., beam steering based on coherent beam combining using square wave dithering algorithm are proposed.

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1. Introduction

High power and good beam quality laser have a wide range of applications in materials processing, medicine and sensor. The successful demonstrations of high power coherent beam combination (CBC) system with active phase-locking of master oscillator power amplifier (MOPA) array [1] show a way to achieve high-brightness beyond the limit of single laser source. Particularly, active phase-locking beam combination methods with single detector, including the stochastic parallel gradient decent (SPGD) [2,3] and single/multi-frequency dithering techniques [4–8], have the potential to overcome the scale limitation of heterodyne technique, and achieve large channel counts with high combining efficiency. The SPGD algorithm applies different sets of phase disturbances with zero-mean and statistically uncorrelated on all channels, and do phase corrections after every disturbance. Via multiple times iteration, the long-time accumulated phase correction approaches the phase error to realize phase locking. The frequency dithering technique applies sinusoidal phase modulations with unique frequency/frequencies, and obtains phase error signals by coherent demodulation. In order to reduce the coherent demodulation error, the integrate time of coherent demodulation tends to be m ($m>1$) times of the period of sinusoidal modulation [6,8], which drops the phase control speed.

In this paper, we propose and demonstrate a novel phase locking algorithm: square wave dithering method. This method uses the same optical system architecture and electronic feedback control strategy as the SPGD and frequency dithering technique but different phase control strategy, and suitable for large scale beam combination. The square wave dithering technology uses dual-level rectangular-wave phase modulation and time division multiplexing instead of sinusoidal phase modulation. Meanwhile, unlike the frequency dithering technique, the coherent demodulation process is no longer required in the square wave dithering method. It has much easier way to implement by digital signal processor, such as field programmable gate array (FPGA). In the experiment, active phase locking of 10 fiber laser beams is successfully obtained, with imposing an additional phase disturbances to mimic the phase noises in the high power fiber amplifiers. The combining efficiency with modulated phase noise is achieved above 97.55% and the accuracy of phase control is improved to $\lambda/42$ rms.

2. Theory

The principle of square wave dithering algorithm is briefly introduced as follows. Assuming that the beam number in the laser array is N and optical fields of each beam are plane wave and identically polarized.

The schematic of phase locking of the 10-channel tiled fiber array is shown in Fig. 1. After an optical wave is split into ten waves

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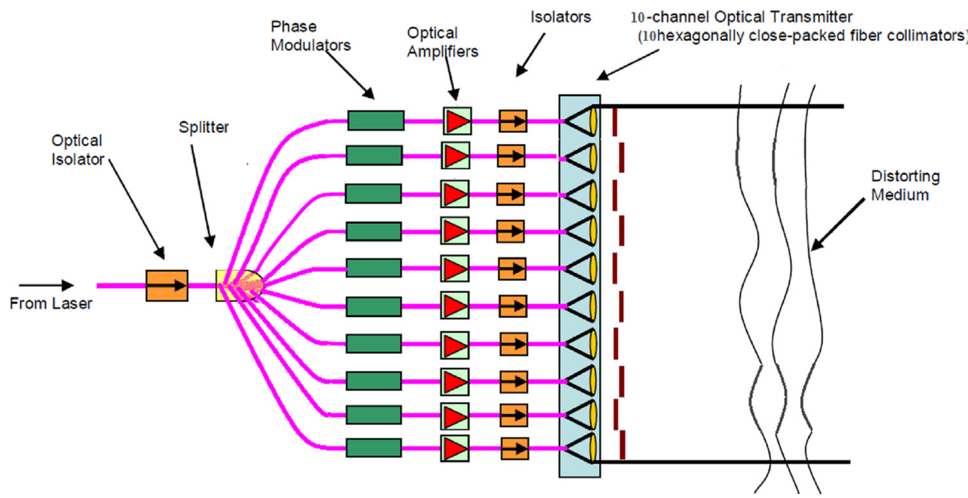

Fig. 1. Schematic of adaptive photonics phase-locked elements all-fiber-component sub-aperture transmitter.

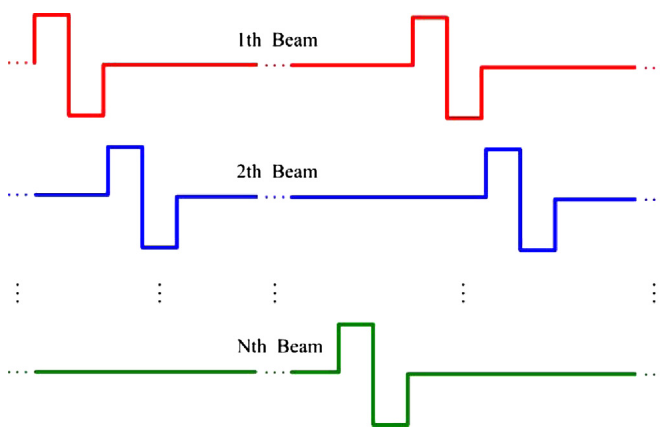

Fig. 2. Phase modulation diagram of dual-level phase dithering method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

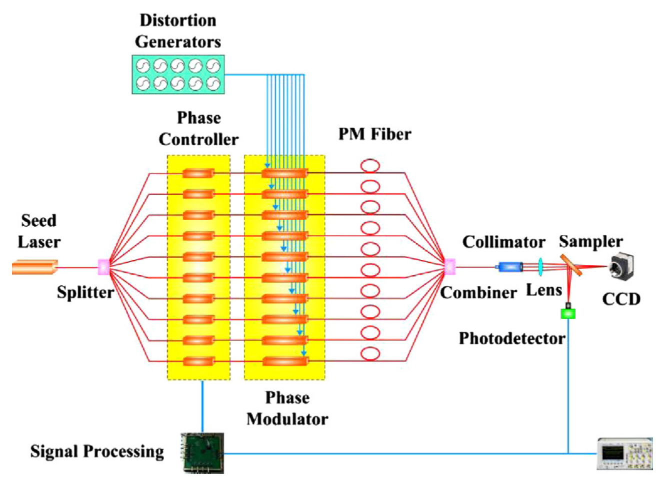

Fig. 3. Schematic of system architecture for coherent combining of 10 beams with additional phase distortion.

and further distorted by the atmospheric aberrations, we have 10 distorted waves $E_{0i}e^{j\phi_i}(i=1,\ldots,10)$.

The photo-detector current of superimposed fields is

$$i_{PD}(\phi_1,\ldots,\phi_N)=\frac{1}{2}R_{PD}A\sqrt{\frac{\varepsilon_0}{\mu_0}}\sum_{i=1}^{N}\sum_{j=1}^{N}E_{0i}E_{0j}\cos(\phi_i-\phi_j). \quad (1)$$

where R_{PD} is response of the photo-detector, A is the active area of the photo-detector, E_{0i} and ϕ_i are the field amplitude and piston phase difference of ith beam. We define three kinds of photo-detector current function as follows:

$$P_i=i_{PD}(\phi_1,\ldots,\phi_i+\psi_i^+,\ldots,\phi_N),$$
$$N_i=i_{PD}(\phi_1,\ldots,\phi_i+\psi_i^-,\ldots,\phi_N),$$
$$Z_i=i_{PD}(\phi_1,\ldots,\phi_i+\psi_i,\ldots,\phi_N), \quad (2)$$

where P_i, N_i and Z_i denote the photo-detector current when the optical phase of ith beam change amount of, respectively. Similar to the frequency dithering technique, we define the phase error signal as

$$S_i=R_{PD}A\sqrt{\frac{\varepsilon_0}{\mu_0}}\sum_{j=1}^{N}E_{0i}E_{0j}\sin(\phi_j-\phi_i). \quad (3)$$

Inserting Eqs. (1) and (3) into Eq. (2), we obtain

$$S_i=\frac{\cos\psi_i^-(P_i-Z_i)+\cos\psi_i^+(Z_i-N_i)+\cos\psi_i(N_i-P_i)}{\sin(\psi_i^--\psi_i)+\sin(\psi_i^+-\psi_i^-)+\sin(\psi_i-\psi_i^+)}. \quad (4)$$

S_i is the same as the time integrated phase error signal of frequency dithering techniques up to certain coefficient differences [4,7]. For sake of simplicity we set $\psi_i=0$, $\psi_i^-=-\psi$, $\psi_i^+=\psi$, then Eq. (4) is further reduce to,

$$S_i=R_{PD}A(\varepsilon_0/\mu_0)^{1/2}\sum_{j=1}^{N}E_{0i}E_{0j}\sin(\phi_j-\phi_i)=\frac{P_i-N_i}{2\sin\psi}. \quad (5)$$

Eqs. (4) and (5) indicate that of the phase error signal of ith beam can be obtained by weighted power dithering of CBC far field via dual-level or tri-level rectangular-wave phase modulation of the corresponding channel, while without the coherent demodulation integration in time domain. Using time division multiplexing by applying the phase modulation on each channel in turn (Fig. 2), the phase error signals of all channels are obtained in a cycle. The phase correction of all channels should be executed simultaneously at the end of the cycle, to ensure locking all piston phases at the same value in static state, which is similar to the single-frequency dithering method [7,8].

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