Self-Synchronous Coherent Beam Combination

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Abstract: A completely novel concept for coherent beam combination is presented. The technique completely eliminates the need for a reference beam resulting in a dramatic simplification of electronic coherent beam combination without any compromise in performance.

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1. INTRODUCTION

To achieve the high brightness’s required for many laser applications it is necessary to phase lock multiple element fiber optical arrays. The intensity and hence the powers available from single-mode optical fibers are limited by optical surface damage or nonlinear optical effects. These limitations can be overcome by coherent beam combining of the output power from multiple optical fibers. Accurate control of the optical phase is required for any multi-fiber approach. In a master oscillator power amplifier configuration, the optical paths of each of the fibers must be locked to within a fraction of the wavelength in order to coherently combine the individual outputs into a single, high-power beam. As a result of time varying thermal loads and other disturbances, active feedback is required in order to provide for coherent addition of the beams from the array elements. There have been a number of experimental and theoretical research efforts addressing the need for very high brightness fiber laser sources. The technical approaches that have been attempted include the optical self-organized[1,2,3], nonlinear optical[4], and RF phase locking methods[5,6,7,8,9,10]. To date RF phase locking techniques have demonstrated both high beam quality and the highest powers[9] of any beam combination technique. All of the RF phase locking methods by other researchers[5,6,7,8,9] have required both an external reference beam and one photodetector per array element. A unique feature of our previous work was the first demonstration of a novel electronic phase locking technique that used only a single photodetector[10]. In this paper, we present the first RF phase locking technique that eliminates the need for a reference beam. This new architecture for coherent beam combination results in considerable simplifications compared to previous RF phase locking systems. For the new method that is called self-synchronous locking of optical coherence by single-detector electronic-frequency tagging (SS-LOCSET) there is no reference beam wavefront to match co-align with the array element wavefronts and in addition only a single photodetector is needed so there is no need to spatially isolate the light from a single array element from adjacent photodetectors. The self-synchronous LOCSET technique provides a dramatic simplification in the experimental system without any compromise in system performance. Furthermore, this is the first phased array locking technique that doesn’t require an external reference beam.

2. SELF-SYNCHRONOUS LOCSET THEORY

In the self-synchronous LOCSET technique[11] all of the array elements are phase modulated at unique RF frequencies in similar manner to the first LOCSET technique[10]. The phase error signal for an individual slave element originates from the RF beat note generated by the interference between the individual array element fields. Therefore, the fields from all of the array elements must overlap on the photodetector to obtain the error signal. A simple means of ensuring this is by imaging the central lobe of the far-field onto the photodetector being used for phase control.

Assuming, that the fields are plane waves and are identically polarized, then the i\textsuperscript{th} array element optical fields, \(E_i(t)\) are,

\[ \begin{align*}
E_i(t) &= E_{i0} \cdot \cos(\omega_L \cdot t + \phi_i + \beta_i \cdot \sin(\omega_i \cdot t)) \\
&= E_{i0} \cdot \cos(\omega_L \cdot t + \phi_i + \beta_i \cdot \sin(\omega_i \cdot t)) , \quad (1)
\end{align*} \]

where \(E_{i0}\) represents the field amplitudes for the i\textsuperscript{th} array element. \(\omega_L\) represents the laser frequency. \(\phi_i\) represents the optical phase of the i\textsuperscript{th} array elements. \(\beta_i\) represents the phase modulation amplitude for the i\textsuperscript{th} array element. \(\omega_i\) represents the RF modulation frequency for the i\textsuperscript{th} array element. When the optical fields from all of the array elements are superimposed on the photodetector and the resulting photodetector current is,

\[ \begin{align*}
i_{PD}(t) &= R_{PD} \cdot A \cdot \frac{E_{i0}}{\mu_0} \cdot \left( \sum_{j=1}^{N} E_j(t) \right) \left( \sum_{j=1}^{N} E_{j0} \right) , \quad (2)
\end{align*} \]
where $R_{PD}$ represents the responsivity of the photodetector, $A$ represents the photodetector area, $E_i$ and $E_j$ represent the electric field of the array element beams, $N$ represents the number of elements in the array, $j$ and $l$ represent summation indices for the array elements.

The phase control signal for each element is extracted from the photocurrent by multiplying the photodetector current by $\sin(\omega t)$ and integrating over a time, $\tau$, where $\omega$ represents the phase modulation frequency of one of the slave elements and the integration time, $\tau$, is selected to simultaneously isolate the individual phase control signals of the slave elements and short enough so that the phase control loop can effectively cancel the phase disturbances of the system. The phase control signal is,

$$S_{\omega} = \frac{1}{\tau} \int_0^\tau i_{PD}(t) \cdot \sin(\omega t) \, dt \quad (3)$$

If $\omega_i = \omega_j$ and if the integration time, $\tau \gg 2 \pi/\omega_i$ and $\tau \gg 2 \pi/(\omega_i-\omega_j)$ for all $i$ and $j$ when $j \neq i$ then the Eq. 3 is to an excellent approximation,

$$S_{\omega} = R_{PD} \cdot \sqrt{P_i} \cdot J_1(\beta_i) \left( \sum_{j=1}^N \sqrt{P_j} \cdot J_1(\beta_j) \cdot \sin(\phi_j - \phi_i) \right) \quad (4)$$

where $\phi_i$ and $\phi_j$ represent the phases of the $j$th array element and the $i$th array elements, respectively. The strength of the demodulated signal is proportional to the square root of the product of the optical powers in the $i$th slave element of the array and the Bessel function of the first kind, $J_1(\beta_i)$. The term in the bracket on the right-hand side is due to the self beating between the $i$th array element and the other slave elements. This term on the right hand side of Eq. 4 contains the phase error term. When this signal is used for the phase error correction signal and serves to stabilize the phases of the array elements self-synchronize with each other to minimize the sum on the right-hand side of Eq. 4. Thus the phase of the $i$th array element is locked to the average phase of the other array elements. In addition, because every array element is controlled by a separate electronic circuit all of the array elements self-synchronize co-operatively to maximize the phase fidelity of the combined array. The phase control signal is amplified and feedback to cancel phase disturbances.

3. CONCLUSIONS

A unique and significant advantage of the self-synchronous LOCSET technique is there is no reference beam, unlike any of the previous electronic phase locking techniques. This results in a much simpler more robust phase-locked array architecture compared to previous phase-locked array techniques. The first theoretical analysis of a novel coherent beam combining technique that offers not only highly accurate and robust phase locking but is also readily scalable to a large number of elements is presented. A detailed development of the theory, conditions for applicability and calculations of the expected signal-to-noise ratio versus number of array elements will be presented.