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First Experimental Demonstration of Coherent Fiber Array Phase Locking without an External Reference Beam

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Abstract: A 3x3 passive fiber and a 3x2 fiber amplifier arrays were phase locked using two novel phase locking architectures. The measured phase error was λ/22 independent of the number of elements locked.
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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. This is the only technique for phase locking fiber arrays that doesn't require an external reference 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]. RF phase locking techniques have demonstrated high fringe visibility and the highest powers of any beam combination technique to date [8]. The previous electronic phase locking techniques all required external reference beams and all of the previous work except for our previous work also required one photodetector for each array element. In this effort, we demonstrate that first that an external reference beam is not necessary and second that in fact no reference beam is needed to electronically phase lock an optical array.

2. SELF-REFERENCED LOCSET THEORY

In the self-referenced LOCSET technique[11] the reference element is not modulated while the slave elements are all phase modulated at unique RF frequencies in similar manner to the first LOCSET technique[9,10]. The phase error signal for an individual slave element originates from the RF beat note generated by the interference between the reference element and the individual slave element fields. The phase control signal for each element is extracted from the photocurrent by multiplying the photodetector current by $\sin(\omega_i t)$ and integrating over a time, τ, where ω_i represents the phase modulation frequency of one of the slave elements and the integration time, τ, 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. If the integration time, $\tau >> 2\pi/\omega_i$ and $\tau >> 2\pi/(\omega_i-\omega_j)$ for all i and j when $j\neq i$ then the Eq. 1 is to an excellent approximation,

$$S_{rii} = R_{PD} \cdot \sqrt{P_i} \cdot J_1(\beta_i)\left(\sqrt{P_r} \cdot Sin(\phi_r - \phi_i) + \sum_{j=1}^{N} \sqrt{P_j} \cdot J_0(\beta_j) \cdot Sin(\phi_j - \phi_i)\right) \quad , \tag{1}$$

where ϕ_j and ϕ_i represent the phases of the jth slave element and the ith slave elements, respectively, P_r and P_i represent the powers of the reference and ith slave elements, respectively. The first term in the brackets on the right hand side of Eq. 1 is due to the beating of the reference field with the field from the ith array element. The second term is due to the self beating between the ith array element and the other slave elements. If the array is well locked then the differences between the slave elements and the reference beam are small and this second increases significantly the strength of the phase control signal. The phase control signal is amplified and feedback to cancel phase disturbances.

3. EXPERIMENT

Figure 1 is a schematic block diagram of the experimental system. MO represents the master oscillator. The laser light from one output of the fiber splitter leg is directed into a fiber coupled EOSpace 1x8 phase modulator. The fiber outputs are connected to the nine single mode fiber collimators in the sparse 3 x 3 array. The central element of the array is not phase modulated and the other array elements are all phase modulated at separate RF frequencies between 100-MHz and 146-MHz. The central lobe of the far field is imaged onto the photodetector and the far field pattern is imaged onto the active area of a CCD camera by lens F2. The demodulation and the routing of the phase control signals for each array element are performed by the signal processing circuits. The phase locked intensity pattern was stable even under relatively strong fiber disturbances. The measured root-mean-square phase fluctuations were $\lambda/25$ when the control loop was closed. The measured rms phase fluctuations remained constant as the number of array elements being locked increased from two to nine elements. The measured root-mean-square phase error is equal to the calculated phase fluctuations, within the experimental error of the measurement, due to the phase modulation in our system.

4. CONCLUSIONS

We present the first experimental demonstration of self-referenced LOCSET. A unique and significant advantage of the self-referenced LOCSET technique is that one of the array elements can be used as a reference beam. This results in a simpler more robust phase-locked array architecture. To date LOCSET is the only optical phase locking method that provides this possibility. Furthermore, this method only requires a single photodetector. The phase locking accuracy was measured to be $\lambda/22$. In addition, the phase locking accuracy is independent of the number of array elements. Finally, to the best of the author's knowledge this is the first phase locking of nine elements by electronic phase locking methods. A detailed discussion of the experimental system, rms phase error measurements will be presented.

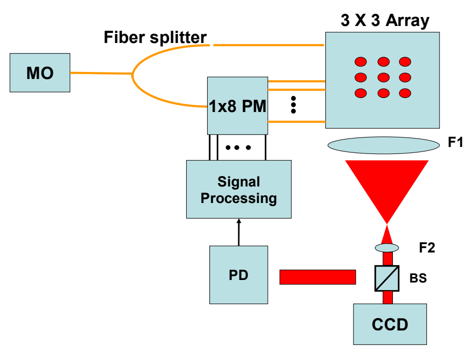

Figure 1. Block diagram of the phase control system. MO presents the master oscillator. F1 represents the lens that focuses the array output into the far-field. F2 represents the lens that images the far-field pattern onto CCD camera and the photodetector, PD. BS represents the beam splitter that separates the beams that are delivered to the CCD camera and the photodetector.

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