Summary

To achieve the high brightness’s required for many laser applications it is necessary to phase lock multiple element optical arrays. Recently, the University of Michigan has demonstrated 810-W of power out of a single mode fiber with a near diffraction limited optical beam. The intensity and hence the power available from a single-mode optical fiber is limited by either optical surface damage or nonlinear optical effects. These limitations can be overcome by coherent beam combining of the output power from multiple optical fibers. We have developed a novel coherent beam combining system that offers not only highly accurate and robust phase locking but in addition is readily scalable to hundreds of elements. Recently, we presented the theory and report the first experiments demonstrating this novel phase locking using this technique in a passive fiber array. Here we report the first demonstration of phase locking of optical amplifier arrays by RF phase modulation.

Accurate control of the optical phase is required for any multi-fiber approach. In a MOPA 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. 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 approaches and RF phase locking methods. To date the self-organized systems have demonstrated phase locking of only 50% to 80% power in the central lobe. In contrast, electronic phase locking has demonstrated high fringe visibility for both passive and active systems. In the previous electronic phase locked fiber arrays, each leg of the array is modulated at the same RF frequency. The light emerging from each leg is then interfered with the light from a reference leg because the same RF frequency is used to modulate each array leg the light from each leg must be sent to a spatially photodetectors. Good fringe visibilities of >94% and hence very low phase errors were measured. However, Abderegg et al. reported that the spatial alignment has stringent requirements even when the fiber-to-fiber spacing was 3-mm. For practical purposes any array locking method must confine most of the array power into a single lobe, this in turn requires the use of a close packed array. The closer the array elements are the more stringent the spatial alignment specifications. Furthermore, scaling to larger numbers of array elements will require tighter alignment tolerances for this approach.

We present the first demonstration of phase locking of 2 and 5 element fiber amplifier arrays using RF phase modulation. Our approach preserves the strengths and simplicity of RF phase locking while providing scaling to very large numbers of elements and simultaneously decreasing the alignment tolerance by over 2 orders of magnitude. We modulate each leg of the fiber amplifier array with a separate RF frequency, thus tagging the phase shift for each leg by a separate RF frequency. In contrast with the previous electronic phase locking techniques, the reference beam is spatially overlapped with all the RF modulated beams fiber leg beams onto a single detector. The phase shift between the optical wave in the reference leg and in the RF modulated legs are measured separately in the electronic domain and the phase error signal is feedback to the LiNbO$_3$ phase modulator for that leg to minimize the phase error for that leg relative to the reference leg. This approach is easily scalable to 100’s of elements because the phase error signals for each leg are separated in the electronic domain versus the optical domain.

A block diagram of the control system used to lock the phase of 2 fiber amplifiers is shown in Fig. 1. The 2 fiber amplifier system is the building block for scaling to multiple fiber amplifier locking. In this system, the reference leg, is unmodulated, while the optical field in the $i^{th}$ slave leg is phase modulated at an RF frequency, $\omega_i$, the optical fields from the reference and slave legs are combined in a 3-dB fiber splitter. The optical fields from the reference and $i^{th}$ slave leg then interfere on the photodetector to produce beat notes, that contain the optical phase difference between the reference and $i^{th}$ slave leg, $\Delta \phi_{in}$. The beat note term for the interference between the reference leg field and the $i^{th}$ leg field is,

$$I_{in}(t) = \eta \cdot \sqrt{P_{r0} \cdot P_{i0}} \cdot \cos \left[ \beta_i \cdot \sin (\omega_i \cdot t) + \Delta \phi_{in} \right], \quad \text{Eq. 1}$$

where $I_{in}(t)$ represents the time dependent portion of the beat note term between the reference field and the field from the $i^{th}$ leg, $\eta$ represents the quantum efficiency of the photodetector, $\beta_i$ represents the phase modulation amplitude for the $i^{th}$ fiber amplifier leg, $\omega_i$ represents the RF modulation frequency for the $i^{th}$ amplifier leg, $\Delta \phi_{in}$ represents the phase difference between the reference and $i^{th}$ amplifier legs. $P_{r0}$ and $P_{i0}$ represent the power in the reference and $i^{th}$ amplifier legs, respectively. If the RF modulation frequencies are separated by more than the control loop bandwidth then coherent demodulation in the RF domain can easily extract the phase error for a single amplifier leg with no significant interference from the adjacent amplifier legs. By coherently demodulating at the RF frequency $\omega_i$ and integrating an error signal proportional to the sine of the optical phase difference, $\Delta \phi_{in}$ is detected. The
demodulation process consists of multiplying the beat note current in Eq. 1 by \sin(o_t t) and integrating over a time long compared to the period of the RF frequency. The error signal for the feedback system, \( E_\epsilon(t_0, \Delta \phi_0) \), is,

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S_\epsilon = \frac{1}{\tau} \int_0^\tau I_s(t) \cdot \sin\left( (\omega_0 t - t) \right) \cdot dt = \frac{e}{2} \cdot \eta \cdot \sqrt{P_0 \cdot P_0} \cdot J_1(\beta) \cdot \sin(\Delta \phi_0), \tag{Eq. 2}
\]

where \( J_1(\beta) \) represents a Bessel function of the first kind of order 1. Note that the amplitude of \( S_\epsilon \) is used as the error signal since it is proportional to the sign of the phase difference between the reference and \( i \)th amplifier legs and it changes sign as \( \Delta \phi_0 \) changes sign. This error signal is then signal processed and feedback to the Li:NbO_3 modulator to control the phase. In our previous research we reported a visibility is 97%, this corresponds to a phase fluctuation of \( \lambda/25 \) in a passive 2 fiber array and we also reported excellent results in locking a passive 5 fiber array. We now extend that work to active fiber arrays. This system stayed locked for phase disturbances of 20,000 waves per second.

For the 5-element fiber amplifier array the system is the same. The reference fiber leg was unmodulated and the other 4 slave fiber legs were modulated at 125, 128, 131, and 134-Mhz. The fields from all 5-fiber amplifiers are superimposed on a single photodetector and the RF beat note signals are demodulated in the electronic domain. The electronic control loop for each slave leg is identical to the electronic control loop in the Figure 1. We will report the results of these amplifier array-locking experiments.

Finally, we also observed the optical power out of both loops while the fiber arrays were jiggled under both free running and locked conditions. As you would expect under free running conditions the power oscillated from zero to 100%, however as soon as the control loop was turned on the intensity stabilized. We report the first demonstration of a fiber array phase locking method that simultaneously provides high accuracy phase locking (\( \lambda/25 \)), can track phase disturbances of 20,000 waves/sec and is easily scaled to hundreds of elements.

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