Practical technique for improving all-fiber coherent combination of multistage high-power ytterbium fiber amplifiers

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1. Introduction

High-power high-brightness laser beams are required for many applications, and there is a continued interest in scaling fiber laser systems up to increasingly higher power levels. Single-mode continuous wave (CW) broad-linewidth fiber amplifiers with ~10 kW average power output have been reported [1]. Unfortunately undesirable effects, such as thermo-optic, amplified spontaneous emission (ASE) and optical surface damage, will inevitably hinder the further average power scaling of CW fiber lasers/amplifiers. For a fiber laser/amplifier working in the pulsed regime, the power scaling is further limited by nonlinearities including self- and cross-phase modulation, stimulated Brillouin scattering (SBS), and stimulated Raman scattering (SRS). Coherent combining of multiple fiber amplifiers by active phase-locking beams is a viable method for power scaling and brightness improvement over the limitations of single-fiber lasers/amplifiers. There have been various approaches reported, which include, but are not limited to, multidithering [2–6], heterodyne detection [7,8], stochastic parallel gradient descent phase control [9,10], and single-frequency dithering [11,12]. In most of the above demonstrations [4,5,11,12], a phase modulator, one of the major components that adds significant cost as well as loss, is required for phasing locking multiple beams. We explore here an all-fiber configuration scheme for realizing coherent combination via direct pump current modulation [3,13]. Compared with state-of-the-art dithering methods we eliminate the requirement of phase modulators in our fiber amplifiers. All optical beams are able to be preserved in single-mode fibers during amplification until it exits the system. There are no optical benches and no sensitivity adjustment, resulting in a simpler and more robust system.
Previously we have successfully applied the aforementioned technique to coherently combine seven Er-doped 1.5 μm, 1 W fiber amplifiers on a few hundred meters long outdoor range [14]. However, it fails to work when applying the same technique to multistage fiber amplifiers as the power outputs are scaled 1 to 2 orders higher. We found that as the pump current was changed for adjusting the phase of the preamplifier output beam, the power input to the power amplifier was also changed substantially. This, in turn, caused an opposite phase change in the power amplifier that canceled, to a large degree, the phase change achieved in the preamplifier. Furthermore, the whole system was prone to ASE because of the unstable input to the power amplifier during phase locking. Both of these effects would prevent coherent phasing of the high-power fiber amplifiers. We overcome that problem by adding a homemade second-stage preamplifier, which is designed to mitigate the phase change as well as the ASE in the power amplifier. By doing so, we improve the phase-locking efficiency from 0% to 80% of time, and consequently demonstrate coherent combination of two single-mode high-gain (>55 dB) fiber amplifiers, each of which has a peak output power of 12 kW, average power of 50 W, 1 MHz pulse repetition frequency, 4 ns pulse width, and 70% optical-to-optical conversion efficiency.

2. Experiment and Analysis

The block diagram of the experimental setup based on a master oscillator power amplifier (MOPA) configuration is shown in Fig. 1.

The master oscillator includes a Lightwave 142 monolithic ring laser to produce a single longitudinal mode laser beam at 1064 nm, two electro-optic modulators (bought from JDS-Uniphase (JDSU)) to chop the CW laser beam at a 1 MHz repetition rate and to generate 4 ns pulses with time-limited bandwidth, and a fiber preamplifier to boost the average power output to 0.4 mW. The optical power from the master oscillator is equally split into four channels with 0.1 mW each with fiber splitters. Two fiber outputs are used as a signal monitor as well as other power amplification schemes for comparison, while the other two fibers are respectively spliced into two separate 50 W level fiber amplifier chains. Each amplifier chain includes a preamplifier that is made of 10 m long Nd-doped 6 μm field diameter single-mode fibers, and about 15 m long single-mode 20 μm diameter fiber power amplifiers made of Nufern’s polarized large-mode-area (PLMA) ytterbium-doped double-clad fibers. Each preamplifier is optically pumped by 818 nm laser diodes (LDs) and its respective power amplifier is pumped by 976 nm LDs. Pump beams of 818 nm are coupled from both ends into the single-mode fibers via wavelength division multiplexing (WDM) fiber couplers, and pump beams of 976 nm are coupled into PLMAs from the output end via 976/1064 dichromirrors. Different sizes of fibers are angle cleaved and spliced together. A thermal expansion technique is used to guarantee mode matching between different sizes of fibers and to minimize the return loss at each connection. Fiber polarization controllers are used between the amplifiers to control the polarization of each beam. The preamplifiers are expected to boost input power from 0.1 to 30 mW, and the power amplifiers push the output power up to 50 W level. Fiber lengths of each amplifier chain are matched within 10 cm accuracy in order to maintain the pulse shape in time domain at the combined output. As shown in Fig. 1, the light output from both amplifier channels are collimated and combined at a beam splitter. The intensity of the combined beams at the far field can fluctuate due to phase variations among these beams. In order to realize coherent combination, we monitor the combined beam with a photodetector (PD) in the other arm of the beam.
splitter. Perfect coherent combination would null out the signal at the PD. Control of the phase is achieved by use of multidither feedback loops \([2,3,13,14]\). The pump currents of the first preamplifiers are dithered with different frequencies in the kilohertz range. The variations in the pump current lead to the refractive index changes of the doped fibers, and thus to phase variations of the amplified signals \([15–18]\). The phase modulation mentioned above turns into intensity modulation of the combined beam at the far field, which leads to voltage modulation in the PD signal at that particular frequency of the channel. Lock-in amplifiers (EG&G) are used to distinguish among the different dither signals, and each beam's output is fed back to the current controlled pump diodes of the respective preamplifier. It is expected that when the control is turned on, the beams shall be locked in phase. The PD feedback signal is at its minimum only when two beams are in phase at the power meter.

The phase modulation capability of each preamplifier was characterized before it was spliced with other amplifiers. A fiber piezo-stretching technique was used to measure the phase change as the function time as the preamplifier was triggered with a stepwise pump current \([16]\). It was concluded that in the saturation regime the phase change of the output was approximately linear with the amplitude change of the step current, with the measured modulation rate of \(0.7\pi/A\) (1.0A modulation current corresponding to \(2.0 \pm 0.5\) mW pump power of the preamplifier in our setup), while the 10%–90% rise time is approximately constant with \(\sim 1.0\) ms.

With only a preamplifier and a power amplifier in each chain, we encountered an issue of losing phase-locking capability. We found that while two beams coming out of each amplifier could be kept in phase at low power level (<1 W), they were hard to be kept in coherence as we increased the power output of each amplifier to the 10 W level. Furthermore, the ASE noises were also observed in the backward direction of the power amplifier at this high power level.

In order to address this, a simple experiment was conducted. The schematic is similar with that shown in Fig. 1, but the second stage preamplifiers have not yet been included, and the lock-in amplifier to the pump current of the preamplifier is disconnected. Figure 2 demonstrates the PD measurement as the function of time at (a) low power level (<0.5 W) and at (b) high power level (>5 W). The series of temporal traces are the relative voltage output of the PD, which is linearly proportional to the optical powers through the pinhole (in front of the PD). When there is no current modulation on the preamplifier, the interferometer output varies from the minimum to the maximum due to phase perturbations (such as from air perturbation, fiber vibration, wavelength drift of pump current, etc.). In our interferometer setup, the PD output is at its maximum if the two beams have a \(\pi\) phase difference and was at its minimum if the phase difference was zero.

The traces marked with 0 and \(\pi\), as shown in Fig. 2, are snapshots of the PD outputs at its minimum and maximum, respectively, during the period of 10 ms. These prerecorded traces would enable us to quantify the phase changes by the pump currents.

If we start to modulate the pump current of one of the preamplifiers with a 180 \(\mu\)s rectangular pulse, as shown in Fig. 2, the associated phase change leads to an amplitude change of the interferometer output. We can deduce the associated phase by comparing the interferometer output with the prerecorded outputs at 0 and \(\pi\) phases. Since the phase perturbation mentioned earlier is normally a relatively slow process (in the tens of milliseconds) compared with the pulse response, the signal change (as the bumps shown in Fig. 2) within the submilliseconds were solely due to the current modulation. We triggered a pulse of modulation current when the initial PD outputs were midway between the maximum and the minimum, and recorded the interferometer output with the scope. A simple mathematic analysis can show that at this level, the phase difference between two amplifiers in the unit of \(\pi\) radians approximates to the power change in the duration of the pulse divided the power difference between maximum and minimum. From Fig. 2(a) we can read that for a pump pulse of 0.45A, the associated phase change is about \(\pi/4\) and the 10%–90% rise time is about 1.0 ms. This measurement was conducted when the fiber amplifiers were in sub-Watt level. It shall be noted that the preamplifier was kept at the saturation regime during the interferometer
measurement. The modulation rate is estimated to be $0.55(\pi/A)$ in this regime.

However, as the output power was scaled up, we can only acquire about $\pi/10$ phase change even with 10 times more pump current, as shown in Fig. 2(b). It should be noted that when the same pump pulse of 0.45 A was used at the high power level (>5 W) as in the (b) condition, there was no phase change observed. The phase modulation rate is estimated to be 0.02$(\pi/A)$, 25 times smaller than the rate at the low power level, while the 10%-90% rise time is about 1.0 ms. Clearly the phase modulation capability deteriorates as the power level increases. Moreover, we also found that there was an unpredictable ASE spectral spike from the optical spectral analyzer (OSA) readout associated with the pump pulses. These experimental results suggest that the phase change induced at the preamplifier had been canceled out in the power amplifier, and that any substantial phase change at high power levels requires a larger pump current change that may induce ASE spikes.

The above phase canceling phenomena can be understood with Kramers-Kronig’s (K-K) relations, which relate the real and imaginary parts of the susceptibility of $\chi'$ and $\chi''$ of the medium. Their relationship can be approximated as $\chi'(\nu) \approx (2(\nu - \nu_0)/\Delta \nu)\chi''(\nu)$, if the frequency of interest $\nu$ is in the vicinity of the resonance frequency $\nu_0$ of the dielectric medium. The resonance frequency is in the band of ultraviolet for the doped fibers used here due to its more dominant absorbing transition than in the other wavelengths [15]. It can be seen from the above equation that if the pump current changes the gain coefficient, which is approximately linear to $\chi''$, it would also change the refractive index, which is approximately linear to $\chi'$. As we increase the pump current of the preamplifier, it changes the refractive index in the fibers of preamplifier, and also increases the gain of the preamplifier. On the other hand, the increased seeded power for a power amplifier decreases the gain of the power amplifier since it is in the saturation regime, which changes the refractive index, according to the K-K relations, of the fibers in the power amplifier in the opposite direction to that in the preamplifier. Therefore, the overall phase change along the fiber amplifier chain is much smaller than it is in the high power level. As the matter of fact, from K-K relations we might conclude that the pump current of the preamplifier will not generate any phase modulation if the total gain, which is the ratio of the power amplifier output to the preamplifier input, is fixed.

However, in reality, the phase change mechanism is much more complicated. First of all, the gain and the phase change are not necessarily linearly related, partially due to the thermally induced phase change [17]. Second, both the gain and the change of refractive indices are spatially distributed, and constrained with different physical mechanisms. Moreover, they are very sensitive to kinds of dopants and doping levels in those doped fibers. More quantitative analysis, however, are beyond the scope of our work.

In order to solve the problem discussed above, we insert a second-stage fiber amplifier between the preamplifier and the power amplifier, as shown in Fig. 1. The technique involves only fiber amplifiers without inserting any delicate or power limiting elements, yet it extends it to high-gain, high-power amplifiers. The design of the second-stage preamplifier, including the pump power of the diodes and the length and the kind of Nd-doped single-mode fiber, was made to reach the following criteria:

(a) The phase change of the beam that propagates through the second preamplifier should be small and not sensitive to the power outputs from the first preamplifier.
(b) The output power of the second preamplifier should be large enough to saturate the power amplifier in order to minimize ASE and be stable enough so that the gain of the power amplifier is independent of the gain of the first preamplifier.

We have tested several kinds of 1063 nm Nd-doped single-mode fibers from different manufacturers, and the Nd-doped single-mode fiber brought from Newport was chosen for making the preamplifier. Figure 3 demonstrated the interferometer output of two fiber amplifier chains at 22 W, with the setup including the second preamplifier. It shows that under the pulse current of ~1.3 A, there was about a $\pi/5$ change. The modulation rate is estimated to be 0.15$(\pi/A)$, and the 10%-90% rise time is about 1.2 ms. It should be noted that the phase change did not decrease much as we increased the output up to 50 W, indicating the influence of the preamplifier on the power amplifier has been mitigated.

Figures 4(a)–4(e) demonstrate the outputs from each individual amplifier chain, which includes first- and second-stage preamplifiers and the last stage power amplifier. The average output powers in (a) demonstrate that we have 50 W output with 71% optical efficiency. Each amplifier delivered 4 ns pulse trains with peak power >12 kW. There is moderate spectral broadening in the pulsed regime as shown in (c), in contrast with no spectral broadening in the CW regime as shown in (b), but no signs of SBS or SRS up to the 50 W power level.

![Fig. 3. Interferometer output of two fiber amplifiers at an output level reaching 22 W.](image-url)
The ASE noise issue is expected to be mitigated with the incorporation of the second preamplifier, as we mentioned earlier. Figure 5 demonstrates that the ASE spectral spikes may occur at the high power level (>5 W) without the second preamplifier, while it is eliminated even at the much higher power output level (>20 W) with the second preamplifier. These ASE spectra were recorded from a monitor fiber that was spliced before the power amplifier in order to monitor the backward photon signals from it.

Finally, we demonstrated coherent combining of two amplifiers by closing the feedback loop. Figure 6(a)

Fig. 4. (a) Measured output powers as a function of the pump powers and currents. (b), (c) The OSA output of the (b: CW; c: pulsed) output beam in the forward direction.

Fig. 5. OSA output of the power amplifier in the backward direction at the different pump power level (a) without the second preamplifier and (b) with the second preamplifier. In (a) the ASE spikes start at around the 15 W of pump power level, while in (b) there is no ASE observed under the same or higher pump power levels.

Fig. 6. PD outputs as the function of the time. The blue curves are observed when the feedback loop is closed. The fiber amplifiers worked in the (a) CW and (b) pulsed regime.
shows that the system is kept in phase 80% of the time in the CW operation. The same architecture was also applied to the coherent phasing of high power amplifiers in the pulsed regime, as shown in Fig. 6(b). Again, the experimental results demonstrate almost the same phasing capability as in the CW regime, keeping in phase about 80% of the time.

Relative power spectral densities before and after phase lock were also acquired by Fourier transforming the PD outputs from time domain to frequency domain, as shown in Fig. 7. The PD outputs were recorded as the amplifiers work at 4 ns pulsed regime and at their maximum average power outputs (~50 W per amplifier). It demonstrates that by turning on the feedback, the phase noise lower than 100 Hz has been mitigated effectively, while those noises in higher frequency regimes are less affected.

3. Conclusion

We have demonstrated multidithering pump current modulation-based coherent combining of two high-power 1 μm fiber amplifier channels, each of which can operate either CW or 4 ns output pulses at 1 MHz repetition rate and 50 W average power. They are built in an all-fiber MOPA architecture. We have identified the major problem in phasing multistage amplifiers at high power levels and provided a solution to it. The system can be kept in phase at least 80% of the time in both CW and pulsed regimes.

There may be two major higher-frequency noises contributing to the 80% efficiency limit. The residual second-harmonic frequency signals can be converted to power noises [2] and they are definitely in the higher frequency regime where the phase locking is less effective. The residual signals can be decreased if we can improve the modulation rate so as to reach the same phase change with less current modulation. Mode instabilities existed in high-power fiber amplifiers would also contribute to the power noises [19,20]. Mode instabilities can be mitigated by decreasing power outputs and (transverse) mode numbers, such as decreasing fiber sizes of power amplifiers, decreasing fiber bending radius, and improving thermal management, etc. Both factors need more quantitative study.

Further combining of tens of such amplifiers should be similar. In the lab we have successfully combined three of them. Combining additional fiber amplifiers was not pursued due to unavailability of additional amplifiers. Scaling up to hundreds would pose a new problem using this technique since every fiber needs an individual phase modulation frequency (~kHz) but the modulation bandwidth of the fiber preamplifier is limited (e.g., ~10 kHz, referring to [18]). To overcome this limitation the recently demonstrated single-frequency dithering technique [11] may be adopted so that the same dithering frequencies are used repeatedly in time sequence.

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References


