Coherently combined master oscillator fiber power amplifiers for Advanced Virgo

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Stable low-noise high-power lasers are indispensable in advancing the strain sensitivity of interferometric gravitational wave detectors. Advanced LIGO and Advanced Virgo are currently under commissioning and require about 200 W of single-frequency laser power, while the future detector design may require up to the order of 500 W. In this Letter, we present the design and, to the best of our knowledge, the first experimental demonstration of the laser system for Advanced Virgo that is based on coherently combined fiber laser amplifiers. We show the long-term performance of two 40 W fiber laser amplifiers, as well as their characterization in terms of beam quality, power noise, phase noise, and beam pointing. Moreover, a simple and compact setup utilizing fibered modulators and actuators for the coherent beam combination of these two fiber laser amplifiers is reported. A combination efficiency of about 96% was achieved, and no spurious noise was observed. © 2016 Optical Society of America

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The quantum nature of light sets a fundamental limit in the strain sensitivity of interferometric gravitational wave detectors [1]. High laser power is desired to advance this so-called standard quantum limit, despite the parallel efforts required in view of the consequent increase in radiation pressure noise, especially at low frequencies where it can dominate.

Gravitational waves have recently been detected for the first time, almost a century after Einstein’s prediction on their existence; the first observation run of Advanced LIGO settled on two gravitational wave detections and a possible candidate [2–4]. Advanced LIGO is being upgraded toward the eventual design sensitivity, where a 220 W solid-state laser is to be used [5].

Advanced Virgo [6] is another gravitational wave detector with a similar strain sensitivity goal. A laser system based on coherently combined fiber laser amplifiers is planned to provide the required power of 175 W, as shown in Fig. 1.

Fiber laser amplifiers are an emerging technology for high-power single-frequency applications: the high surface-to-bulk ratio of fibers facilitates heat dissipation, and the waveguide structure is beneficial to decent beam quality and efficient beam combining [7,8]. Early efforts on beam combining generally set their focus on power efficiency, while it was reported recently the coherent beam combination of two 10 W single-frequency fiber laser amplifiers with almost no additional noise [9].

This Letter demonstrates the coherent beam combination of two 40 W single-frequency fiber laser amplifiers using Mach–Zehnder interferometry. The concept is not new but, to the best of our knowledge, our results show not only the highest combined power, but also the best noise performance of coherently combined fiber laser amplifiers reported to date. Moreover, it should be noted that instead of transient results that are commonly reported, this Letter incorporates rigorous long-term characterization in view of the continuous operation required in Advanced Virgo and other gravitational wave detectors.

High power is only one of the many rigorous requirements on the lasers for gravitational wave detectors. Power noise, frequency noise, and beam pointing fluctuations can all introduce noise to the gravitational wave signal readout and, therefore, have to be treated carefully. Most notably, the relative power

Fig. 1. Advanced Virgo laser system design features coherently combined fiber laser amplifiers seeded with an NPRO.
noise budget derived from the strain sensitivity design goal and interferometer configuration, with an additional safety margin of factor 10, plunges down to as low as $2.35 \times 10^{-9} \text{ Hz}^{-1/2}$ in the gravitational wave detection band from 10 Hz to 10 kHz and $8 \times 10^{-9} \text{ Hz}^{-1/2}$ in the MHz modulation band at the input of the Michelson interferometer [10–12].

As shown in Fig. 1, the laser system is stabilized in terms of power and frequency before being injected to the Michelson interferometer. The Pre-Mode-Cleaner and the Input-Mode-Cleaner are triangular ring cavities that not only transmit a high-purity TEM$_{00}$ beam but also attenuate laser noise whose Fourier frequency lies outside the cavity linewidth. An autocorrelation system is also engaged to stabilize laser beam pointing. The projection of laser noise budget at the input of the Pre-Mode-Cleaner is relieved accordingly. The most stringent requirement in terms of relative power noise is found in the MHz modulation band with a value of $4.75 \times 10^{-9} \text{ Hz}^{-1/2}$ at 6.27 MHz. The typical (10 kHz/f) HzHz$^{-1/2}$ frequency noise of an NPRO laser [13], which is sufficient for the requirement of Advanced Virgo, and the beam pointing fluctuation budget found in [10] are taken as references in noise budget.

Injection locking and master oscillator power amplifier are two general techniques for low-noise high-power solid-state lasers. In recent years, the advances in fiber laser amplifiers have popularized the so-called master oscillator fiber power amplifiers [14–16]. In this Letter, we use fiber-coupled NPRO lasers (Innolight Mephisto) as the master oscillators to seed two fiber laser amplifiers (Azur Light Systems), hereinafter referred to as Amplifier 1 and Amplifier 2. The amplifiers are very similar to the system described in [17], which consist of two stages: the preamplifier which amplifies an input signal of >20 mW to about 1 W, and the power amplifier which delivers >40 W.

The two fiber laser amplifiers were tested and monitored over several thousand hours with constant current injection. The output power time series are plotted in Fig. 2. We note that, except for the periods marked with crosses (×), the amplifiers were running quasi-continuously with our best effort. The interruptions in the data curve are due either to the temporary shutdown (protective or intended) of the amplifiers or the failure of the data acquisition system.

Amplifiers 1 and 2 were placed in different labs for power trend monitoring. The measured output power of Amplifier 2 fluctuated more than that of Amplifier 1. This is mostly due to the more frequent shutdowns of Amplifier 2 (either by the protective circuit or intended for other measurements), and that a few hours were required for the output power to stabilize every time the amplifier was restarted, as plotted in Fig. 3. The excess power fluctuation on the startup is likely due to the combined effect of the polarization fluctuation of the fiber amplifier and the optical isolator downstream [18]. Besides, there were more activities in the lab of Amplifier 2.

A loss rate of about 1 mW per hour, or 8.8 W per year, was found for both amplifiers based on the linear fits of the time series between 3600 and 6400 h. After the long-term operation, we were able to gain about 8 W of output power in a linear fashion by increasing the pump diode current.

Figure 4 shows the power noise spectrum of Amplifier 2 estimated over 60 h with 15 min measurement intervals. The Advanced Virgo requirement is plotted for comparison. This is derived by projecting the transfer functions of the passive filtering of optical cavities and the active stabilization of control loops (Fig. 1) onto the specifications [10] at the input of the Michelson interferometer. We note that the requirement at lower frequencies corresponds to the gravitational wave detection band (around 10 Hz to 10 kHz) while, at higher frequencies, it corresponds to some discrete modulation frequencies (around 6 MHz to 100 MHz) for the sensing and control of the Michelson interferometer.

The phase noise of Amplifier 2 was measured using Mach–Zehnder interferometry. By multiplying the Fourier frequency, the results are represented in terms of frequency noise and plotted in Fig. 5. The typical frequency noise of NPRO is plotted for comparison [13]. The excess noise between 1 kHz and 10 kHz originated from the preamplifier stage is believed to result from both the environmental acoustic and the electronic noise of the pumping laser diode driver based on spectral resemblance and coherence measurements.
Figure 6 shows the normalized beam pointing stability $[\varepsilon]$ whose square denotes the fractional power coupled into the TEM$_{01}$ and TEM$_{10}$ modes due to small misalignments [13,19], of both amplifiers measured with quadrant photodiodes.

A fraction of the laser beam of Amplifier 2 was coupled into a polarization-maintaining single-mode fiber (PM980-XP) with $>88\%$ efficiency. Given the $3.6\%$ Fresnel reflection loss for each uncoated FC/APC fiber facet, this infers that $>95\%$ of the beam is matched to the fiber LP$_{01}$ mode that highly resembles ($>99\%$) the TEM$_{00}$ mode in free space.

The power noise and beam pointing fluctuation of Amplifier 1 were also measured to give similar results.

A dither-locked Mach–Zehnder interferometer was implemented for coherent beam combination (Fig. 7). After some pick-off plates for diagnostics, about $35\ W$ was sent from each fiber laser amplifier to the Mach–Zehnder interferometer. The fringe contrast was maximized to $92\%$ with tip-tilt mirrors, inferring a $96\%$ combination efficiency, a value that agrees with the abovementioned TEM$_{00}$ mode content of $>95\%$.

The power noise and beam pointing fluctuation of Amplifier 1 were also measured to give similar results.

The phase dynamics of Amplifier 2 were measured using a similar setup to Fig. 7 with Amplifier 1 replaced by a fiber. The differential phase drift was about $2200\ rad$ in $15\ h$ before reaching equilibrium, as plotted in Fig. 8. In this measurement a deliberate asymmetry was introduced to lock the interferometer by thermally tuning the frequency of the NPRO laser.

Since Amplifiers 1 and 2 are essentially identical, one could expect that most of their phase drift takes place in common-mode, and only some residual takes place in differential-mode. It has been reported, however, that mismatches of $10\%$ may be expected from nominally identical fiber laser amplifiers [7].

To reduce the differential phase drift between the two arms of the Mach–Zehnder interferometer, we minimized the asymmetry by inserting a compensation fiber in one arm to compensate for the length introduced by the fiber EOM and the fiber stretcher in the other arm. The final path length difference was measured to be about $0.5\ m$ by tuning the NPRO laser frequency and observing the induced phase drift.

The differential phase drift time series between Amplifier 1 and 2 in the coherent beam combination setup are plotted in Fig. 8. A continuous phase-lock up to about $20\ h$ was possible, primarily limited by the shutdown of individual fiber amplifiers and environmental disturbances such as manned lab activities.

The combined beam was characterized in terms of power noise and beam pointing stability. Since Amplifier 1 was phase-locked to Amplifier 2, the phase noise of the combined beam is expected to resemble that of Amplifier 2 (Fig. 5).
Fig. 9. Relative power noise spectrum of the combined beam.

Fig. 10. Beam pointing fluctuation spectrum of the combined beam (dashed gray); Amplifier 1 (dotted line) and Amplifier 2 (solid line) versus Advanced Virgo requirements (dashed black).

likely due to the changes in the coupling from beam pointing fluctuation to the power noise in photodetection.

The increase at frequencies between about 500 Hz and about 6 kHz are considered as the combined effect of the coupling from beam pointing fluctuation to power noise in photodetection and the finite collinearity of the two combining beams with which the phase actuation reshapes the wavefront and steers the beam. This is suggested by the beam pointing stability measurements shown in Fig. 10, while considering the additional phase noise of Amplifier 2 in Fig. 5. Contributions from the residual amplitude modulation of phase actuation are also to be considered.

The additional peaks in the MHz range of the power noise spectrum of the combined beam are related to dither-locking. The even harmonics of the 14 MHz modulation frequency are naturally present when the Mach–Zehnder interferometer is locked to the bright fringe, while the fundamental and the odd harmonics should be nulled. Their observation in the spectrum may be explained by the residual amplitude modulation of the fiber EOM and DC offsets in the phase lock loop. The frequencies of these peaks can be arbitrarily chosen such that they do not interfere with Advanced Virgo requirements.

We assessed the performance of two 40 W fiber amplifiers and characterized their noise properties. A compact setup using fiber-based frontends for the coherent beam combination of fiber amplifiers is reported. Despite the more-than-twofold gap toward the required power level, which may be amended by either more powerful units or simply more combining units, the noise performance of the combined beam is satisfactory.

More powerful laser amplifiers are desired to limit the number of combining beams since not only the combined power, but also the overall failure rate scales with number. This may sound like a retrogradation to coherent beam combination, as there are already functional >200 W single-frequency lasers for Advanced LIGO [5]. Nevertheless, new techniques and concepts are very likely a must to go beyond such a power level to reach the >500 W level required in future detector designs such as the Einstein Telescope [20]. Fiber laser amplifiers are certainly appealing candidates for the power scaling per unit; cryogenic lasers are another possibility [21], and coherent beam combination is always a workaround at the cost of system complexity.

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