Beam combining of ytterbium fiber amplifiers
(Invited)

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Fiber lasers are well suited to scaling to high average power using beam-combining techniques. For coherent combining, optical phase-noise characterization of a ytterbium fiber amplifier is required to perform a critical evaluation of various approaches to coherent combining. For wavelength beam combining, we demonstrate good beam quality from the combination of three fiber amplifiers, and we discuss system scaling and design trades between laser linewidth, beam width, grating dispersion, and beam quality. © 2007 Optical Society of America

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1. INTRODUCTION

High-power laser beams are required for many applications, and there is a continued interest in scaling laser systems up to increasingly higher power levels. The most demanding applications require that a good beam quality be maintained at all power levels. Unfortunately, as power levels increase, undesirable thermo-optic effects frequently degrade the beam quality. Fiber-laser technology is well-suited to overcoming this problem since the waveguide nature of a fiber dominates over thermo-optic effects, and the ratio of the surface area to volume of a fiber is conducive to efficient cooling. Even given these advantages, it is desirable to increase the system power levels beyond what is possible with a single fiber laser. One promising technology that is being studied to achieve this is to combine a large number of relatively lower power beams into a single high-power beam. The addition of N high-quality beams will then increase the power by a factor of N, and the resulting beam quality will be determined by the method used for beam combining.

Beam-combining technologies can be categorized into three main groups [1]: (1) side-by-side, (2) coherent beam combining, and (3) wavelength beam combining (WBC). For all three geometries, an N-element array will provide N times the power, but only the second two types can also provide an N-times increase in the overall radiance of the system, where radiance is defined as the power per solid angle divided by the source aperture area.

Side-by-side beam combining is the simplest form of incoherent beam combining where no effort is made to control the phase or frequency of individual elements. The combined power and the size of the source aperture are both proportional to N while the far-field divergence is that of a single element, so the radiance for a side-by-side geometry can be no better than that of a single element [2]. Practical implementations include laser diode arrays, and laser arrays used in inertial-confinement fusion systems. We will not discuss the side-by-side beam combining approach here, but will focus on the other two implementations of beam combining where both the power and radiance can scale linearly with the number of elements N.

Coherent beam combining is implemented by forcing all elements of an array to operate with the same frequency spectrum and with the same phase so that when the beams are overlapped, the electric fields add to provide constructive interference. Although the source aperture increases with the number of elements N in tiled implementations, the far-field solid angle decreases proportionally to N, and the power increases with N so the overall radiance is proportional to N.

WBC uses an array where each element is operated at a different wavelength. The near-field and far-field beams are then overlapped with a dispersive element such as a diffraction grating. In this case, the source aperture and far-field solid angle both remain constant as the number of elements is increased so the radiance is proportional to the power, which scales as N.

Fiber lasers and diode lasers are particularly amenable to beam-combining configurations because of their modularity and ease of building tightly packed arrays. We will now discuss coherent beam combining and WBC in more detail. Rather than providing an exhaustive review of the field [1–8], we will be focusing on recent experimental work of implementations using ytterbium (Yb) fiber amplifiers and some practical design considerations for building such systems.

2. COHERENT BEAM COMBINING OF YTTERBIUM FIBER AMPLIFIERS

An overview of different approaches for achieving coherent beam combining can be found in Ref. [1] and will not be repeated here, although they broadly fall under two categories: passive and active phase-compensation techniques. Specific implementations include evanescent-
wave coupling [6–16], common-cavity coupling [17–38], compensation of phase errors using phase-conjugate elements [39–54], and phase detection with active compensation techniques [55–67]. These demonstrations range from subwatt levels [9,17,56,60,62], to 10 W levels [10,20,55,67], to >100 W levels [57–59]. There is one common aspect to all coherent combining approaches, whether active or passive, that we will address in this paper. That common characteristic is undesirable variations in the optical phase, which we will refer to as optical phase noise. For array elements to interfere constructively, the relative phase errors must be small, typically less than $\sim \lambda/10$ for the least demanding applications and better phase alignment requirements for more demanding applications. Regardless of whether coherent combining is done with a passive method, or with an active method, the relative phase noise between elements will determine whether combining is done successfully.

Measurements of the optical phase noise are fundamental in identifying sources of phase noise, which are required to critically evaluate mitigation strategies. Noise-source identification is information that cannot generally be derived from simpler measurements such as the broadening of the optical linewidth after passing through an amplifier. Knowledge of the optical phase noise is important whether an actively or passively beam-combined system is used. An example for how this information is used in the implementation of an actively controlled phased array is to determine actuator bandwidth and range requirements. In passive phase-locking approaches, this information can be used to critically assess whether the passive phase-locking mechanism has sufficient bandwidth and dynamic range to use a given element effectively. To this end, we extend previous work on 10 W fiber amplifiers [55] to modestly higher powers (30 W), but more importantly, we provide a more thorough characterization of the phase noise.

We have performed optical phase-noise measurements of a commercial 30 W Yb fiber amplifier [68] using the setup shown in Fig. 1. Our particular commercial amplifier requires a seed linewidth of at least 60 GHz in order to operate stably so we have used an amplified-spontaneous-emission (ASE) seed source that is filtered to a 60 GHz linewidth. This is split into two paths. One branch is used to seed the amplifier, and the other is used as a reference arm in a Mach–Zehnder interferometer arrangement [55]. A fiber and free-space delay line (100 m) is placed in the reference arm in order to match the path lengths to within the coherence length of the ASE source (1 mm). An acousto-optic (AO) frequency shifter (100 MHz) is placed in one of the arms of the interferometer in order to provide a heterodyne detection signal that is measured with a photodiode having >100 MHz bandwidth. The photodiode signal is demodulated in phase ($I$) and in quadrature phase ($Q$). The negative tangent of the ratio of $I$ and $Q$ yields an unambiguous value for the optical phase for all phase angles, which makes it possible to track the phase variation over an arbitrarily large number of waves [55]. Another advantage of using this detection scheme is that the phase measurement is insensitive to fluctuations in laser power since amplitude fluctuations cancel out to first order in the ratio of $I$ and $Q$.

Figure 2 shows a typical evolution of the optical phase $[\phi(t)]$ over 200 ms taken after the amplifier had reached thermal steady state. There is a clear indication of large low-frequency components in the few-hertz range along with a much higher frequency noise of roughly 1 rad in magnitude. Performing a fast Fourier transform (FFT) on this data (and other long-time records ranging up to ~5 min time span) shows the spectral characteristics of the phase noise in more detail (see Fig. 3). It becomes clear that there is a mechanical resonance at approximately 100 Hz along with a lower-amplitude broad set of resonances at ~1 kHz. Also plotted in this graph is the frequency-dependent integrated phase noise. This quantity represents the cumulative rms phase variation for all frequencies above the frequency of interest. For frequencies where the integrated phase noise is very small, it is not necessary to provide for correction of phase errors, so this plot is helpful in determining bandwidth requirements for correction of phase errors that are above some desired level.
where $S(v) = \text{FFT}[\phi(t)]$ = phase-noise spectral density, and $f_{\text{max}}$ = maximum frequency used for the integration. Theoretically $f_{\text{max}} = \infty$, but in practice it is set to a frequency where $S(v)$ is dominated by the measurement noise floor.

This type of plot is useful in determining actuator requirements for an active control system, but one must be careful in interpreting it. If, as suggested earlier, we wish to keep the phase error less than $\lambda/10$ (i.e., 0.6 rad), the integrated phase noise seems to indicate that a control-loop bandwidth of $\sim 1$ or 2 Hz would be adequate. Looking at the time series in Fig. 2, we see that the width of the trace is roughly 0.5 to 1 rad over time periods of $\sim 1$ ms, which is marginally larger than our desired maximum phase error of 0.6 rad so a control loop with only 2 Hz bandwidth would not be adequate. From this, it appears likely that a control loop would need to have sufficient bandwidth to suppress the resonance peak at 100 Hz. The apparent contradiction in bandwidth requirements comes about because the spectral-density plot is showing rms values, whereas the time series is more effective in highlighting maximum deviations, non-Gaussian, and nonstationary noise. It is the maximum deviations and spurious noise that need to be accommodated in a phase-control system regardless of whether it is passive or active.

A more quantitative way of looking at the nonstationary noise can be illustrated by looking at the phase variation over a specified time interval and looking at that time interval throughout a long data set. For example, we could tabulate the phase change over all possible 1 ms time windows in the data set. If this procedure is repeated for various time-window lengths, we can plot the maximum and rms phase changes during those time windows as shown in Fig. 4. Here the rms phase excursion exceeds $\lambda/10$ (0.6 rad) for times longer than 20 ms and for this 8 s section of data the maximum phase excursion exceeds $\lambda/10$ for time windows longer than $\sim 50 \mu s$ suggesting a control-loop bandwidth more than 10 kHz. We should point out that the rms values are found to be mostly independent of the data set length, but the maximum values tend to become somewhat larger as the length of the data set is increased. This is not unexpected since longer data sets will tend to capture large, low-probability events better than short data sets will. Neither the technique used in Fig. 3 nor the one used in Fig. 4 should be used in isolation. They complement each other and provide the design engineer two different ways of looking at the phase-noise characteristics of a particular amplifier configuration.

We should point out that many spectral characteristics above a few hertz that we have identified can be attributed to mechanical sources. These include cooling fans and mechanical resonances of optical mounts. Additional optical phase noise can be attributed to acoustic and thermal sources. In other words, the phase-noise spectrum shown here is highly dependent on system configuration rather than on the fundamental physics of fiber amplifiers. This is likely to be the case for any engineered system: appropriate packaging and isolation from environmental noise, including vibration and acoustic noise, will be required in order to minimize these noise sources, which dominate at frequencies above a few hertz. Thermal variations in the fiber, mostly caused by changes in the amplitude of pump light (e.g., during turn-on), will be the dominant noise source below a few hertz.

For some coherently combined applications, it is important to maintain phase lock even during the turn-on and warm-up times. Figure 5 shows the phase evolution dur-
element in the oscillator is effectively placed at the focal efficiency is important. The diagram illustrates how each is an acceptable design choice even when good system efficiency of the amplifiers so a somewhat lossy oscillator. For example, system efficiency is determined by the demands on the power amplifiers to merely adding power, which is forgiving on the scale of 10\(\mu\)m rather than on maintaining a phase accuracy that corresponds to fractions of a micrometer. This has been borne out in demonstrations of beam combining of 100-element diode arrays with near-diffraction-limited performance [73], and with high-power performance at hundreds of watts from a few fiber lasers [77,78].

As with coherent beam combining, fiber lasers represent an ideal building block for WBC. We will present here recent results on the combining of three polarization-preserving 30 W commercial fiber amplifiers [68]. Rather than concentrating on reaching the highest possible power, we investigate design considerations for scaling these types of systems to large numbers of elements while maintaining good beam quality.

The basic setup is depicted in Fig. 6 where a master-oscillator power-amplifier (MOPA) configuration is chosen in order to define the temporal and spectral characteristics of the system at low power levels. This reduces the demands on the power amplifiers to merely adding power, and it allows for more flexibility in the design of the oscillator. For example, system efficiency is determined by the efficiency of the amplifiers so a somewhat lossy oscillator is an acceptable design choice even when good system efficiency is important. The diagram illustrates how each element in the oscillator is effectively placed at the focal plane of a spectrometer. The end mirror and grating in the oscillator provide feedback at a different wavelength for each element. Light is then coupled from each oscillator element to its own amplifier. A similar spectrometer arrangement is constructed on the amplifier outputs causing the light to be beam combined after the grating.

It is important that the “spectrometer” in the oscillator cavity and the spectrometer at the output of the fiber amplifiers are identical. For a small number of elements in a proof-of-principle experiment, this can be done in an ad hoc manner with individually adjustable mirrors, but in order to provide a plausible method for scaling to large numbers of elements, there must be a repeatable technique for mounting the fibers. Figure 7 shows the amplifier fibers mounted in a silicon v-groove array. This provides a stable and reproducible method of packaging elements in both the oscillator and on the amplified outputs. The elements are located on a 500 \(\mu\)m pitch allowing for 16 elements in the v-groove assembly shown, although only three adjacent ones are utilized in this experiment. Polarization alignment of the fibers is not critical for WBC configurations as long as the dispersive element is not strongly polarization dependent. In this case, the polarization axes of the fibers are aligned to

### 3. WAVELENGTH BEAM COMBINING OF YTTERBIUM FIBER AMPLIFIERS

WBC is an idea that historically has not received as much attention as coherent beam combining, but interest in the technology is increasing rapidly [69–84] primarily because of the less demanding design requirements for building such systems. This comes about because the system performance is determined by geometrical optics that is forgiving on the scale of 900 radians/second rather than on maintaining a phase accuracy that corresponds to fractions of a micrometer. This has been borne out in demonstrations of beam combining of 100-element diode arrays with near-diffraction-limited performance [73], and with high-power performance at hundreds of watts from a few fiber lasers [77,78].

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within ~3° of each other, which maintains good diffraction efficiency from the grating. The reproducibility in positional and rotational alignment is sufficient to obtain good beam quality on the combined beam. The mode-field diameter of the light exiting the fibers is ~15 μm so the divergence is shallow enough that a plano-convex lens (100 mm focal length) can be used as the transform lens without suffering from significant aberrations. A 1740 line/mm dielectric diffraction grating [85] is used as the dispersive element. It is mounted in a near-Littrow configuration with ~3° deviation angle and has a single-polarization efficiency of 92%. Figure 8 shows the quality of the amplified and combined beam having $M_y^2 = 1.4$ (combining plane), and $M_y^2 = 1.3$ (vertical plane), which are the same values as for a single element.

Figure 9 shows the quality of light at the output of the amplifiers, which matches the input spectrum. The amplifier that is operating at the central peak of 1065 nm is operating at its gain center and is able to produce the manufacturer specified 30 W of power. The other two amplifiers are off their gain centers sufficiently so that they are only able to produce 25 W of output power. The three amplifiers-combined average power is then 73 W after the dielectric grating.

The spectrum of each element has two or three dominant lines attributable to different modes of the fiber-coupled laser diodes that are used as the gain media in the master oscillators. The lines are separated by the free spectral range of the laser diode cavity. To broaden the linewidth of the lasers, the diodes are operated as pulsed sources at ~5 MHz with ~50% duty cycle. This line broadening is required in order to be compatible with the input linewidth requirements of the commercial fiber amplifiers that we are using (~60 GHz).

The linewidth requirement imposed by the particular amplifier being used is one factor that needs to be considered in the overall WBC design. To maintain good beam quality, the dispersion angle off the grating needs to be small relative to the natural diffraction angle that results from the size of the beam. The dispersion angle is the angular spread of the diffracted beam as a result of the spectral linewidth:

$$\sin^{-1}[(\lambda + \Delta/2)g - \sin(\theta_i)] - \sin^{-1}[(\lambda - \Delta/2)g - \sin(\theta_i)] \leq \frac{4\lambda}{\pi d},$$

where $d =$ beam width, $\lambda =$ laser wavelength (1065 nm), $\Delta =$ laser linewidth (0.2 nm), $\theta_i =$ incident angle of light on the grating (~66°, near Littrow), and $g =$ the grating period (1740 lines/mm). Given our 60 GHz (0.2 nm) line-width, it is possible to choose an appropriate beam width in the beam-combining dimension so that a good beam quality is maintained. This has been accomplished by using a cylindrical microlens array at the output of the amplifier fibers to collimate the light in the beam-combining dimension only (see Fig. 7). The light in the vertical dimension is allowed to expand until it reaches the transform lens where it is collimated. This results in a beam that is ~1 cm tall (out of plane) by 0.5 mm wide (beam-combining plane) at the transform lens and at the grating. After the diffraction grating the beam is recircularized with a pair of cylindrical lenses. The use of an elliptical beam on the diffraction grating keeps the beam width small in the combining dimension so that good beam quality is maintained after combination, and it reduces the power density relative to a circular beam of equal width in order to avoid problems with thermal distortion. With our operating parameters the power density on the dielectric grating is ~1 kW/cm² with no evidence of degradation in the beam quality as a result of thermal effects. Figure 10 illustrates a design trade space between beam width, linewidth, and grating dispersion that is necessary in order to maintain a beam quality of $M^2 < 1.4$. These lines are obtained by multiplying the right-hand side of expression (2) by $M^2 - 1$, changing the inequality to an equality, and then solving for various values of $g$, $\Delta$, and $d$. As the operating point moves below the lines, the theoretical value of $M^2$ approaches 1.0. Our operating position is at 60 GHz linewidth and 0.5 mm beam width giving a best-case theoretical $M^2$ value of 1.4, which agrees with the experimental result. A second line is also shown to illustrate the parameter trade space for a grating with lower dispersion (800 lines/mm).

Narrow-linewidth fiber amplifiers have been built in research laboratories where linewidths of <60 kHz have been demonstrated at >500 W of power [86], and similar commercial products may be available in the near future.
for implementation in an actively controlled phased array. Actuation bandwidths are found to be modest and highly system dependent, but the required actuation range is dominated by thermal effects in the fiber covering hundreds of waves during turn-on and warm-up. Alternatively, range requirements can be met with lower range fast snap-back actuators operating with a low duty cycle.

Wavelength beam combining has been demonstrated with good beam quality using three commercial amplifiers having a large linewidth. Scaling such systems up to large numbers of elements can be accomplished using silicon v-groove arrays to mount the fiber ends in a stable and reproducible manner. The versatility of wavelength-beam-combined systems is highlighted by looking at the trade space between laser linewidth, beam size, grating dispersion, and desired beam quality. Such systems can be designed with a compact size even up to very high average power.

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REFERENCES AND NOTES

68. IFG Photonics YAR-30K-1065-LP polarized Yb fiber amplifier with ~40 dB of gain and 30 W saturated output at gain center.
85. The dielectric grating was manufactured at Lawrence Livermore National Laboratories for use in chirped-pulse compression.
87. IPG Photonics, 50 Old Webster Road, Oxford, Mass. 01540, USA (personal communication).
88. Nufern, 7 Airport Park Road, East Granby, Conn. 06026, USA (personal communication).
89. The grating is mounted in a near Littrow configuration. This means that the area illuminated on the grating is roughly a factor of two larger than the cross-sectional area of the laser beam.