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Multi-kilowatt diffractive coherent combining of pseudorandom-modulated fiber amplifiers

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Abstract. We report efficient coherent beam combining of five kW-class fiber amplifiers seeded with pseudorandom phase-modulated light, using a 1×5 diffractive optical element (DOE). Each fiber amplifier channel was path length matched, actively polarized, and provided approximately 1.2 kW of near diffraction-limited output power ($M^2 < 1.1$). A low-power sample of the combined beam after the DOE provided an error signal for active phase stabilization. After phase stabilization, the beams were coherently combined via the DOE. Notably, a total output power of ~ 5 kW was achieved with 82% combining efficiency and excellent beam quality ($M^2 < 1.1$). The intrinsic DOE splitter loss was 5%. Additional losses due in part to nonideal polarization, amplified spontaneous emission content, uncorrelated wavefront errors, and fractional beam misalignments contributed to the efficiency reduction. Overall, multi-kW beam combining of pseudorandom-modulated fiber amplifiers was demonstrated for the first time. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.55.9.096101](https://doi.org/10.1117/1.OE.55.9.096101)]

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1 Introduction

Stimulated Brillouin scattering (SBS) is the lowest threshold optical nonlinearity in single-frequency and narrow-line-width continuous-wave fiber amplifiers. Single frequency, in this context, refers to an optical wave whose spectral linewidth is less than the intrinsic gain bandwidth of the spontaneous Brillouin scattering process. Typically in Yb-doped fibers, the spontaneous Brillouin bandwidth is ~ 50 MHz, and thus, single-frequency Yb-doped fiber amplifiers possess coherence lengths on the order of meters or greater. Consequently, these types of amplifiers are well suited for utilization in coherent beam combining (CBC) architectures due to the relaxed tolerance on the path length matching requirement among the various channels. Unfortunately, the maximum output that can be extracted from such amplifiers has been limited to < 1 kW, due primarily to the challenge of suppressing SBS.^{1,2} In contrast, the challenge of suppressing SBS in narrow-linewidth amplifiers is less demanding. Here, the effective spectral linewidth can be 2 to 3 orders of magnitude greater than the spontaneous Brillouin bandwidth. Although the coherence length can be as short as 1 mm, CBC of high-power, narrow-linewidth fiber amplifiers has been demonstrated.³ For that matter, spectral beam combining (which presents its own set of challenges with respect to the linewidth) has also been demonstrated for these types of amplifiers.⁴

Phase modulation has become the preferred method of suppressing SBS in high-power, narrow-linewidth fiber amplifiers. With the modulation period set at much shorter times than the acoustic phonon lifetime or the light traverse time, large SBS suppression factors can be obtained.⁵

Typically, white noise source³ (WNS) and pseudorandom bit sequence^{6,7} (PRBS) have been the prevalent phase modulation techniques for kW-class fiber amplifiers. Recently, in a direct comparison conducted at the kW-level in Yb-doped amplifiers, PRBS phase modulation was shown to provide superior SBS suppression to that provided by WNS.⁷ In that case, a 1034-nm kW-class fiber amplifier was demonstrated at a modulation frequency of 2.5 GHz through PRBS.

Furthermore, through the use of a 50/50 beam splitter, CBC of two 150-W PRBS-modulated fiber amplifiers was successfully demonstrated.⁶ Here, the discrete spectral lines, indicative of a periodic phase modulation, cause a re-coherence effect where the lasers periodically come back into phase. Particularly, this property may potentially simplify path length matching complexities in fiber laser CBC systems. CBC generally falls under two subcategories as shown in Fig. 1: tiled and filled aperture approaches. The latter subcategory is sometimes realized through the utilization of a diffractive optical element (DOE),³ which provides a uniform fill factor for the combined output beam. While tiled array systems can potentially be extended to phased array platforms,⁸ they may exhibit nonuniform fill factors, which contribute to far-field side lobes that limit the optical power in the central lobe. Regardless, in order to achieve efficient beam combining, optical path length matching and phase locking need to be implemented in order to attain coherence among the various channels.

In this work, we extend CBC of fiber amplifiers driven by PRBS phase modulation to the multi-kW level. We demonstrate CBC of five commercial kW-class fiber amplifiers using a DOE. It is well known that DOE-based beam splitters are convenient optical components for dividing an input beam into N output beams with precise angular spacing at angles that represent the diffractive orders of the structure. Similarly, if mutually coherent beams are incident on the

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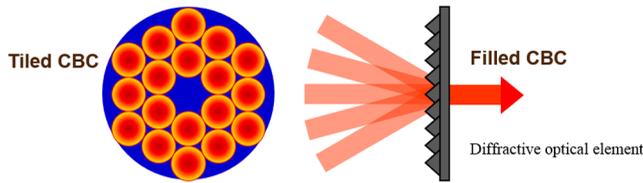


Fig. 1 Tiled and filled aperture CBC. The latter typically utilizes a DOE.

DOE at the proper angles and with appropriate phase matching/locking, the DOE can function in reverse as a beam combiner. As such, diffractive CBC of high-power fiber amplifiers has been demonstrated in the combined 2.4-kW regime with WNS-modulated fiber amplifiers.³ Toward that end, we herein report CBC of five ~ 1.2 -kW PRBS-modulated fiber amplifiers using a 1×5 DOE. Notably, a combined output power of ~ 5 kW was attained with 82% combining efficiency and near diffraction-limited beam quality ($M^2 < 1.1$).

2 Kilowatt-Class Fiber Amplifiers

Five commercial kW-class fiber amplifiers were utilized for the coherent combining experiments. These NuKW amplifiers from Nufern⁹ are nonpolarization maintaining and exhibit electrical-to-optical efficiencies of 35% to 36%. Based on a master oscillator power amplifier (MOPA) configuration, as shown in Fig. 2, a single-frequency nonplanar ring oscillator (NPRO) operating at 1064 nm from JDS uniphase was used to seed the five channels. A PRBS generator and a fiber-coupled LiNbO₃ electro-optic modulator (from EOSPACE) were then used to broaden the effective linewidth of the seed. Here, a modulation frequency of 10 GHz and $2^9 - 1$ PRBS pattern were applied. At this modulation frequency, the coherence lengths of the amplifier outputs were expected to be approximately equal to those of the outputs had the amplifiers been driven with an WNS possessing a spectral full width at half maximum (FWHM) of 10.65 GHz.⁶

After spectral expansion, a small in-line fiber amplifier was constructed to amplify the seed signal before insertion into a 2×8 fused fiber splitter. The splitter provided identical narrow-linewidth signals for each of the five fiber amplifiers. At the applied modulation frequency, little backward power was measured at 1.2 kW for each of the amplifiers. Figure 3 displays a plot of the backward power as a function of output power for one of the amplifiers. As shown, the dependence is linear, which is indicative of operation below the SBS threshold. In comparison, when an

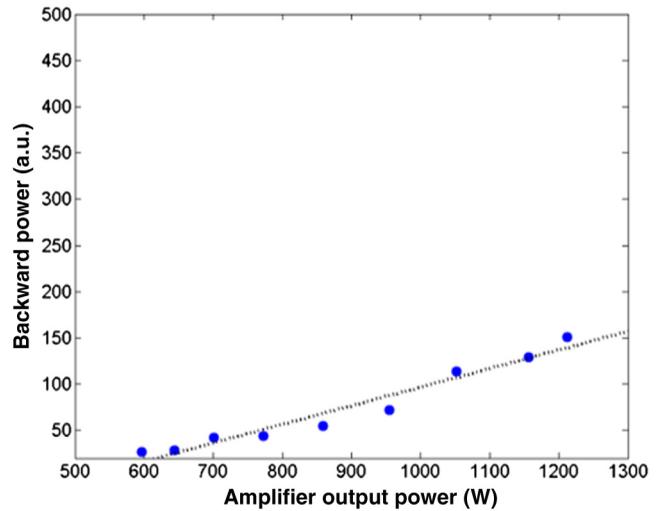


Fig. 3 Backward power versus output power for one of the NuKW amplifiers driven with a $2^9 - 1$ PRBS pattern at a frequency of 10 GHz.

WNS was used to phase modulate the seed, a spectral FWHM of 14 GHz was required to achieve similar results.

Fiber-coupled electro-optic phase modulators were inserted into each of the channels to apply both small amplitude radio frequency (RF) phase dithers and perform piston phase corrections in our phase lock control board. Subsequently, tunable variable delay lines were inserted that can match the optical path lengths between fiber channels and submillimeter tolerances. A polarization tracker module with integrated controller from General Photonics was utilized for linear polarization locking. The polarization controller outputs were then used as inputs for the NuKW fiber amplifiers. Particularly, accurate phase stabilization, path length matching, and linear polarization control are critical for efficient coherent combining.

To verify the suitability of the PRBS-modulated amplifiers for CBC, we conducted measurements of the spectral linewidth, forward output spectrum, and beam quality of each amplifier. A Fabry–Perot interferometer (FPI) was employed to measure the FWHM linewidth. The FPI possesses a free spectral range of 30 GHz with a resolution of ~ 200 MHz. Figure 4(a) shows the FPI-measured output spectra of the PRBS-modulated signal of one of the amplifiers at 7 W (red-dotted curve) and 1100 W (blue-dashed curve), respectively. We note that no spectral broadening was observed at >1 kW and a FWHM linewidth of ~ 8.8 GHz was recorded. Notably, the measured linewidth agrees well with the expected FWHM value for a 10-GHz

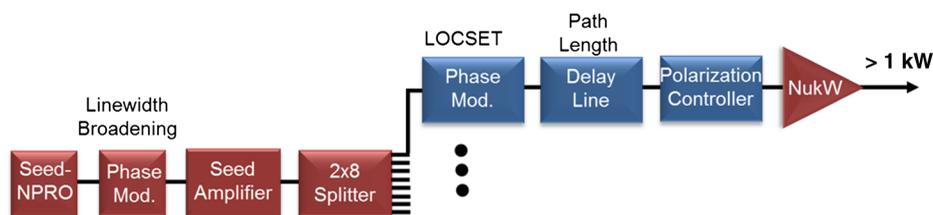


Fig. 2 MOPA block diagram for the five-channel DOE combining. LOCSET phase modulator, variable delay line, and polarization controller were used for phase stabilization, path length matching, and polarization locking, respectively.

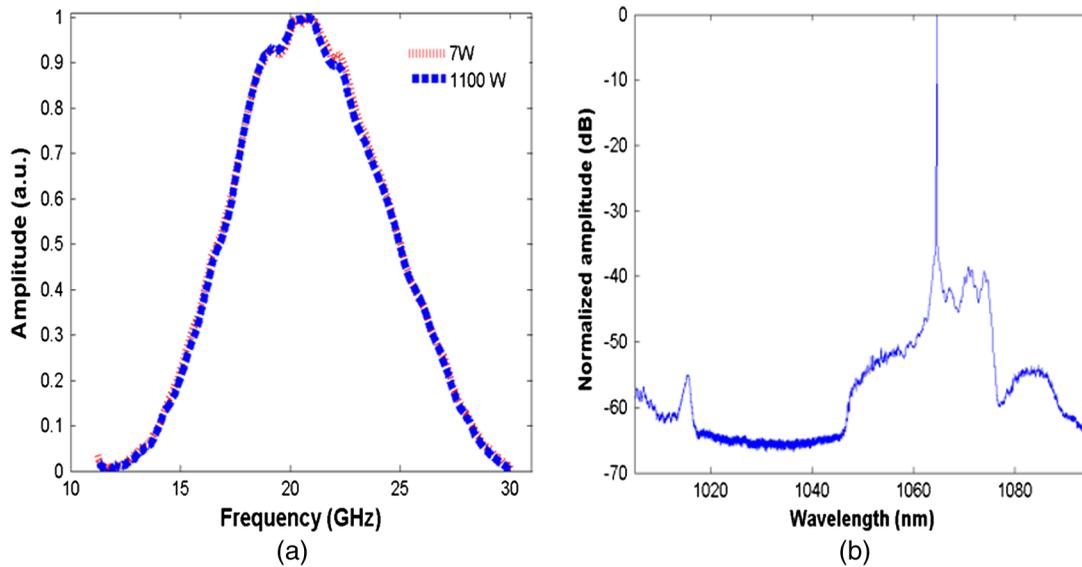


Fig. 4 (a) FPI linewidth measurement at 7 W (red dotted) and 1100 W (blue dashed), respectively. (b) Wide-range (100 nm) forward spectrum captured by OSA at 1100 W. We note no spectral broadening was observed at high power.

modulated PRBS signal with a sinc² spectral distribution. Similar results were obtained for the other amplifiers.

In contrast to the high-resolution FPI measurement, the OSA with a resolution of 0.01 nm (~3 GHz at 1064 nm) can provide a long range capture (100 nm) of the amplifier spectral content. The forward spectrum at 1100 W, shown in Fig. 4(b), displays an amplified spontaneous emission (ASE) content of approximately 1.8%. Although the measured FPI and OSA spectra are shown here for one of the amplifiers, similar spectra were recorded for the other amplifiers with no spectral broadening and roughly 2% average ASE content.

Another key requirement for efficient beam combining is near diffraction-limited beam quality. High-power amplifiers utilizing large mode area fibers may be susceptible to transverse modal instability, leading to sharp and sudden degradations in beam quality. Therefore, we conducted beam quality measurements for each NuKW amplifier using a Thorlabs M^2 beam analyzer. The measured M^2 values were less than 1.1 at 1100 W for each amplifier. Accordingly, pictures of the beam profiles for each amplifier at 1100 W are shown in Fig. 5. Particularly, we have not observed any indication of modal instability at this power level. Overall, the beam quality and forward spectra for all five fiber amplifiers were well suited for beam combining.

3 Multi-Kilowatt Beam Combining Results

A schematic of the DOE combining experimental setup is shown in Fig. 6. Initially, the beams were individually collimated and a low-power sample of each amplifier was utilized for active polarization locking using the aforementioned polarization controllers. After polarization locking, polarization extinction ratios (PERs) of 15 to 16 dB were measured for each fiber amplifier. Next, the five beams were directed onto the reflective DOE by a pair of turning mirrors at the appropriate diffraction angles. At 1064 nm, the angle between diffracted orders was 8.87 mrad. The high-reflection (HR)-coated DOE had dimensions of 15 mm × 15 mm × 6 mm on a fused silica substrate. The continuous surface relief profile DOE was uncooled similar to other DOE combining experiments.^{3,10} Significantly, similar HR DOEs have been shown to exhibit ~17 ppm absorption¹⁰ and high-power handling capabilities comparable with HR-coated mirrors.³

The DOE combines most of the power into the $m = 0$ diffractive order, with the remaining power diffracted into the higher orders ($m > 0$). As such, a high-power handling copper beam block was inserted after the DOE to capture the stray light. The DOE was tilted slightly so the combined output beam is separated from the input beams and reflected out of the plane of diffraction.

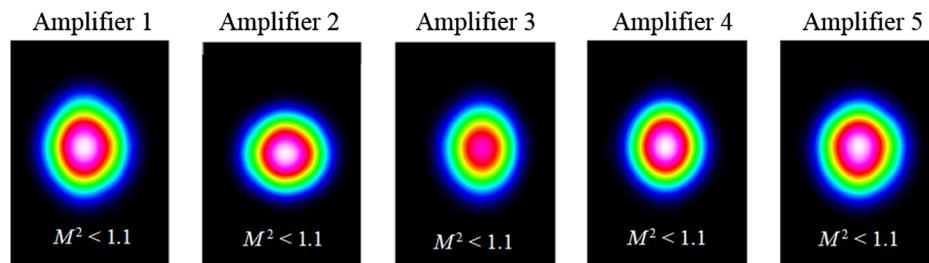


Fig. 5 Measured beam profiles for each of the NuKW amplifiers at 1100 W. All five laser beams exhibited excellent beam quality with M^2 values less than 1.1.

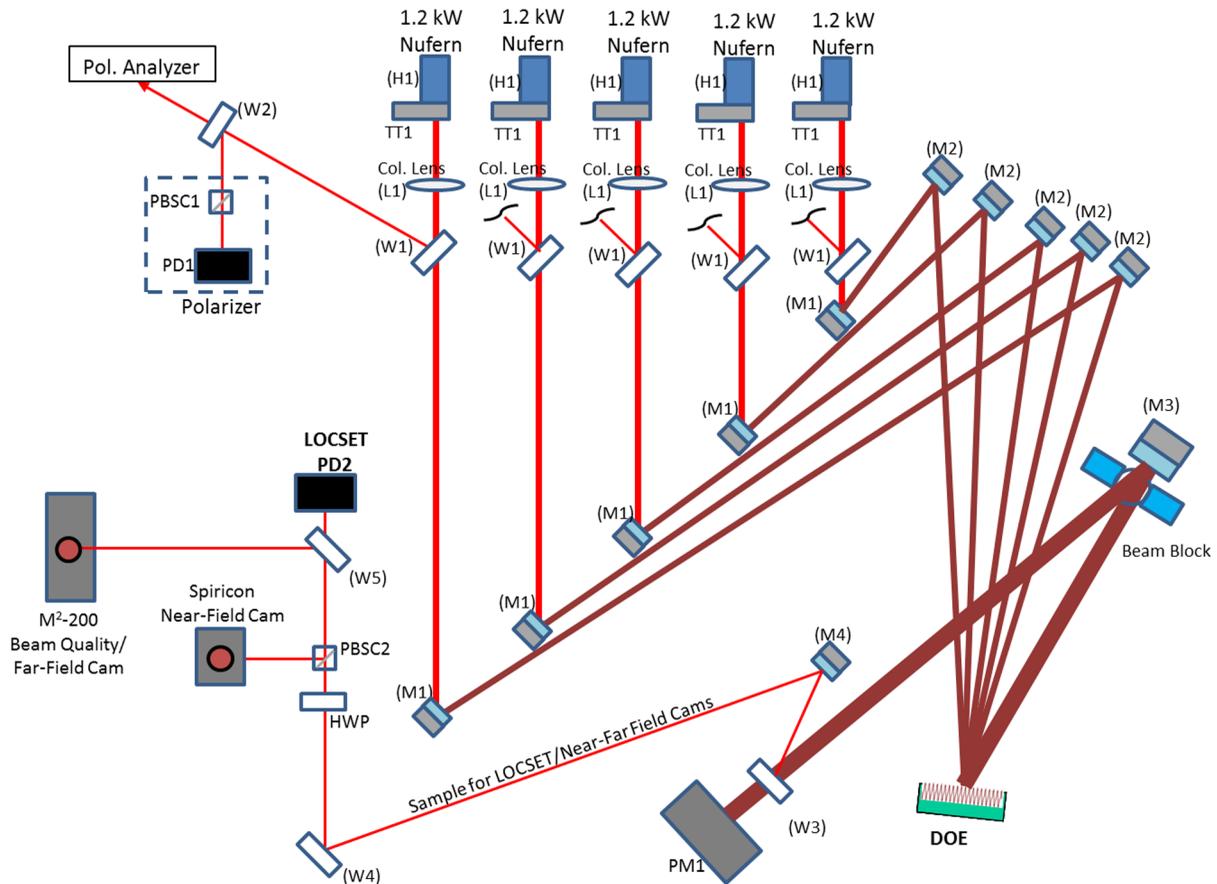


Fig. 6 Schematic of the 1×5 DOE beam combining setup. After collimation, samples of each beam were used for polarization locking and a sample of the combined output beam was used for LOCSET phase locking and beam quality analysis. M1–4: reflective dielectric mirrors, W1–5: beam sampling wedges, HWP: half-wave plate, PBSC: polarizing beam splitter cube, PD1–2: photodetector, and PM1: power meter.

Subsequently, a low-power sample of the combined output beam after the DOE was utilized for active phase stabilization and beam quality analysis. Active phase control was performed via locking of optical coherence via single-detector electronic-frequency tagging (LOCSET),¹¹ where a small RF phase dither or “tag” was applied to each channel through sinusoidal phase modulation. In practice, to minimize residual phase errors, the RF modulation amplitude is kept on the order of 1/10th of a radian or approximately 1/60th of the optical wavelength. These corresponding phase dithers are then measured at the LOCSET photodetector (PD2) as an interference beat note that contains the phase information needed for phase locking. Consequently, error correction signals are applied to each phase modulator to ensure optimal phase matching between all the amplifiers in the system.

After polarization and phase locking, the beams were coherently combined via the 1×5 DOE. Ultimately, a total output power of 4.9 kW was achieved with 82% combining efficiency. A plot of the combined output power versus input power is shown in Fig. 7. The beam quality of the combined output beam was also measured as shown in Fig. 8. The differences between the x and y curves are due in part to the ~ 4 -deg angled end caps added to each fiber output. Specifically, near diffraction-limited beam quality was attained with a measured M^2 value of less than 1.1. It is important to note that the beam quality and combining

efficiency were nearly constant at all power levels, thus inferring the absence of major thermal effects in the system.

We note that the overall combining efficiency is constrained by the cumulative effect of various aberrations

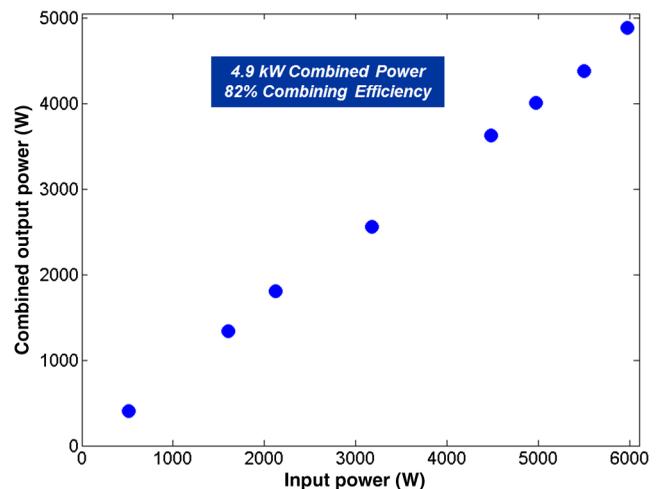


Fig. 7 Input power versus combined output power for the five-channel beam combining. An output power of 4.9 kW with 82% combining efficiency was demonstrated.

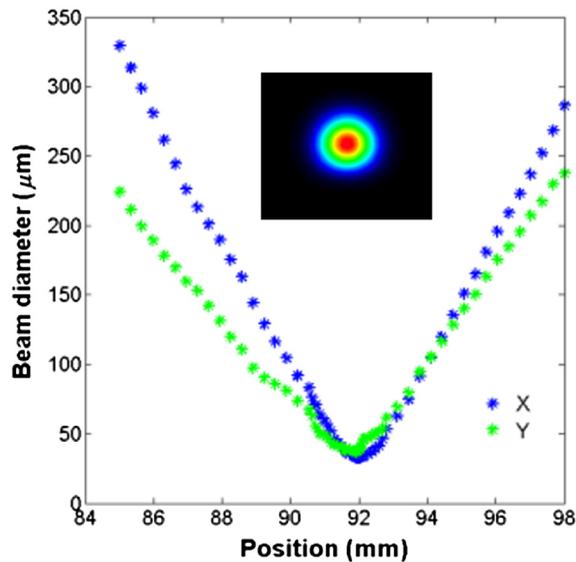


Fig. 8 Near diffraction-limited beam quality was measured with an M^2 of <1.1 . The inset shows the beam profile of combined output beam.

and mismatches between the fiber amplifiers.¹² For example, the 1×5 DOE has an intrinsic splitter loss of $\sim 5\%$ when used as a combiner, with the remaining power diffracted into the higher orders. This is due to the low DOE channel count where there are less degrees of freedom to optimize the phase profile. Specifically, higher efficiencies of $\sim 97\%$ to 99% have been demonstrated with larger DOE channel counts from $N = 9, \dots, 81$.¹³ Similarly, losses due to non-ideal polarization contributed to a reduction in efficiency. As a result, the measured 15- to 16-dB PERs contribute approximately 2% to 2.5% loss. Residual phase errors from LOCSET, previously measured to be approximately $\lambda/60$, also impart an approximate 1% to 1.5% loss in combining efficiency.¹¹ The combining loss due to amplifier ASE content was roughly 1.6%. Moreover, other losses were believed to be due in part to slight optical misalignments/beam displacements and uncorrelated wavefront errors.

We note both higher combined powers and higher efficiencies can be attained through utilization of DOEs with higher channel counts. In addition, we have observed PERs of >20 dB with newer commercial polarization controller modules and incorporation of polished end facets should mitigate some of the uncommon wavefront errors. These attainable improvements may yield combining efficiencies approaching 90% for future experiments. For example, coherent combining of 64 fibers has been reported in the literature.¹⁴ In general, coherent combining has no established channel limit but constraints due to cost, complexity, and packaging will ultimately bound channel counts. Nevertheless, to our knowledge, the resulting 4.9-kW output with 82% efficiency represents the highest combined power for a pseudorandom-modulated fiber amplifier system.

4 Conclusion

Five commercial kW-class fiber amplifiers with near diffraction-limited beam quality were seeded with pseudorandom phase-modulated light to suppress SBS. Through application

of a 10-GHz ($2^9 - 1$) PRBS pattern, the five amplifiers were coherently combined with a 1×5 DOE. Here, a low-power sample of the combined beam after the DOE provided an error signal for active phase stabilization via LOCSET. Additionally, each fiber amplifier consisted of a polarization controller and variable delay line for polarization locking and optical path length matching. Overall, a combined output power of ~ 5 kW was attained with 82% combining efficiency and near diffraction-limited beam quality ($M^2 < 1.1$). Accordingly, this represents the first multi-kW class beam combining demonstration of fiber amplifiers seeded with PRBS phase-modulated light.

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