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Coherent combining of high-power Yb fiber amplifiers*

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ABSTRACT

Commercial 0.5-kW Yb-doped fiber amplifiers have been characterized and been found to be suitable for coherent beam combining. Eight such fiber amplifiers have been coherently combined in a tiled-aperture configuration with 78% combining efficiency. The power-in-the-bucket vertical beam quality of the combined output is 1.25 times diffraction limited at full power. The beam-combining performance is independent of output power.

Keywords: beam combining, Yb-doped fiber amplifier, optical phase control

1. INTRODUCTION

Coherent combining of Yb fiber amplifiers is a promising technique to increase the overall output power [1]-[7] from efficient laser sources. The most common coherent combining architecture is to split the light from a common master oscillator (MO), feed it into multiple phase controllers and fiber amplifiers, and phase-lock the outputs from all the amplifiers using an active control system. Although multi-kW output power has been demonstrated from Yb fiber lasers whose bandwidth is several nm wide [8], narrower optical bandwidth fiber amplifiers are needed for beam-combining applications. Recently, the beam combinability of a 1.4-kW Yb-doped non-polarization maintaining fiber amplifier was demonstrated in which 25-GHz linewidth was used to mitigate SBS effects [9]. Here, we report on the beam combining characteristics of lower-power (0.5 kW) polarization-maintaining fiber amplifiers, which need less optical linewidth (~10 GHz) to suppress SBS, easing path-length-matching requirements. Eight of these fiber amplifiers are coherently combined with high efficiency and excellent beam quality at 0.5-kW per amplifier.

2. FIBER AMPLIFIER CHARACTERIZATION

Commercial 0.5-kW fiber amplifiers from two different manufacturers were characterized. The key measurements of interest for beam combining include output power, beam quality, preservation of spectrum, polarization purity, coherence, and phase noise. The amplifiers' spatial outputs typically have M^2 on the order of 1.1 with polarization extinction ratios of around 20 dB.

To test for preservation of spectrum and coherence, these amplifiers have been seeded with one of two inputs. One is a filtered amplified-spontaneous-emission (ASE) noise source. The other is a single-frequency laser followed by an RF-noise-source-driven phase modulator [10]. Although both techniques are effective at generating broadband seeds, the former has both amplitude noise and phase noise, while the latter has phase noise and a constant intensity. Both are tested with the fiber amplifier to better understand the amplifier's behavior. The input power in either case is ~ 5 mW and the input optical bandwidth is ~10 GHz. This broadened input bandwidth is necessary to overcome SBS but is still sufficiently narrow so that the output coherence length is longer than the thermally induced path-length changes in the fiber amplifier.

Previously, significant four-wave mixing (FWM) frequency generation has been shown to degrade coherence in amplifiers with output as low as tens of watts [11]. Significant power-dependent frequency generation is also observed when the ASE source is used, as shown in Fig. 1 (left). This is because the effective refractive index n_{eff} is modulated by the optical intensity (I) via the nonlinear index n_2, $n_{eff} = n_o + n_2 * I$, and causes effects such as FWM, self-phase modulation (SPM) and cross-phase modulation (XPM). Thus, any variation in optical intensity leads to a time-dependent phase and the generation of new frequency components. Since the phase-modulated seed has constant intensity, its nonlinear phase is also constant and does not lead to new frequency generation. Fig. 1 (right) shows the amplifier optical spectra at various output powers. No spectral broadening is observed. Because this amplifier exhibits strong n_2-nonlinearity, we use the phase-modulated source for subsequent work described here.

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To demonstrate the amplifiers' applicability to coherent beam combining, we measure their coherence and phase noise. Fig. 2 shows the experimental setup for the amplifier coherence measurement and the experimental results for one fiber amplifier. A 5-mW, 10-GHz phase-modulated optical source is used to seed the 0.5-kW amplifier. A fraction of this seed is tapped off and used to interfere with the amplifier output after power equalization and path-length and polarization matching. Both the input and the output taps are coupled into a fiber coupler to ensure mode matching. Fringes are observed because of mechanical and thermal drifts. The 96% visibility shows that the amplifier keeps the same frequency content and preserves the signal coherence between its input and output. The remaining 4% is due to a combination of imperfect power equalization and polarization drifts.

To ascertain that such fiber amplifiers are coherently beam combinable, one must also measure their phase noise to determine the required bandwidth of the control electronics. Because the phase controllers such as electro-optic (EO) and acousto-optic (AO) modulators have low power-handling capabilities, they must be placed at the input of the high-power fiber amplifiers. Thus, any control loop will experience a loop delay that corresponds to the propagation time inside the high-power fiber amplifier. Since the fiber-amplifier length can be on the order of tens of meters, this propagation delay can be hundreds of nanoseconds. This delay sets up an upper limit to the bandwidth of the feedback system for phase stabilization.

The phase noise was characterized using a heterodyne measurement similar to those reported previously [2, 7, 12]. The seed laser is split into two. One part is frequency-shifted by 100 MHz by an AO modulator and used as the reference beam. The second part is used as the seed laser for the amplifier. A small portion of the amplifier output is split off and combined with the reference beam in a 4-port fiber coupler. The nominal 100-MHz beat frequency from the coupler output is detected, and demodulated by the same reference RF oscillator that drives the AO shifter to obtain the I and Q components. The ratio of the I and Q demodulation signals corresponds to the tangent of the phase shift, which makes it possible to track the phase excursion beyond a half-wave without the ambiguity that is present with only a single demodulation output. Unwrapping of phase is done in post-processing. Fig. 3 shows the measured phase noise at 15 W and at 0.5 kW. The integrated phase noise falls off very sharply around ~200 Hz. Thus, phase-locking of such amplifiers requires feedback electronics with nominal kHz bandwidth and is not limited by the propagation delay inside the amplifiers themselves. Furthermore, there is virtually no difference in the phase noise between the two powers below 200 Hz. Therefore, the phase noise is not dominated by fiber-amplifier nonlinearity or by thermal effects for noise frequencies above a few Hz, similar to previous comparisons between low-power and high-power operation [7]. This result is in contrast to the results in [9], which found significant nonlinear AM-PM conversion when the amplifier's amplitude noise is a few percent and amplifier power is over 1 kW.

3. COHERENT BEAM COMBINING

Eight of these fiber amplifiers were beam combined in a linear-array tiled-aperture configuration shown schematically in Fig. 4. This system uses a linewidth-broadened master oscillator as a common input to the fiber amplifiers. The master-oscillator output is split and sent through eight phase modulators used for phase control and adjustable delay lines used for path-length matching. The outputs from the delay lines are used as inputs to the high-power fiber amplifiers. The outputs from the fiber amplifiers are collimated by a microlens array to increase the fill factor. The output from the microlens array is sampled, with the sample going through a lens to transform to the far field. A slit is used to look at the on-axis intensity with a photodiode. The electrical signal from the photodiode is sent to the phase controller. A stochastic parallel gradient descent (SPGD)-based [13] control system phases the individual fiber amplifier with respect to each other by applying signals to the phase modulators [6]. SPGD is a hill-climbing algorithm that works to maximize the on-axis far-field intensity by applying appropriate sets of small dithers to the phase modulators. The SPGD phase controller was implemented in a FPGA, which enables a dither frequency up to 300 kHz. $LiNbO_3$ electro-optic phase modulators actuate on the phase using a dither magnitude of $\lambda/40$.

The individual fiber outputs had free-space 1-mm-diameter, 6-mm-long endcap terminations fused to the output pigtails. These endcaps had a 3-degree angle polish and an AR coating to reduce backreflection to the amplifier. The eight endcapped outputs were aggregated in a silicon V-groove array. This V-groove array had a pitch of 1.5 mm. A microlens array does aperture filling to increase the fraction of power in the far-field central lobe. This microlens array has a focal length of 17.5 mm and an individual beam has a Gaussian beam radius of 0.5 mm at this microlens array. The path lengths of the fiber amplifiers were matched to better than 0.1 cm to accommodate the 10-GHz linewidth of the system.

Figure 5 shows the far-field intensity patterns for combining the eight fibers at different power levels per fiber and shows that the far-field pattern is essentially independent of the output power. The less-than-unity fill factor leads to side lobes. At the highest power, 0.5 kW/fiber, the fraction of power in the central lobe is 58%, while at 0.125 kW/fiber this fraction is 57%. This compares with a calculated fractional power in the central lobe of 68%, for and output with uniform phase and the experimental near-field intensity profile. Figure 6 shows the far fields across the beam combining direction with only a single fiber operating and with all eight fibers operating. Ideally the on-axis far-field intensity should increase as N^2, where N is the number of elements. The experimentally observed increase is 50, leading to a beam combining efficiency of 78%. Nonidealities include power inequality among the fibers [14], imperfect polarization purity, imperfect path length matching, errors in the arraying of the output fibers causing differences in far-field pointing among the individual beams, differences in collimation caused differences in focal length within the microlens array and endcap length, residual phase error, and higher-order-mode content. The estimated errors based on measurements are summarized in Table 1. Some of these errors are additive while others need to be rolled together in a root-sum-square (RSS) manner so the total cannot be derived by simply either summing or RSS.

Table 1. Summary of beam-combining inefficiencies.

Nonideality	Error magnitude	Efficiency loss (%)
Power inequality	10% peak-to-peak (pp)	<1
Polarization purity	20 dB purity and <5 degrees pp fiber-to-fiber rotation	2
Path-length matching	<1 mm pp	1
Far-field pointing	13% rms relative to full angle divergence of single fiber	10
Collimation	2% pp focal length error	9
Residual phase	$\lambda/40$ rms	2.5
Higher-order modes	<7% fractional power	<7
Total		**22**

Another measure of the ideality of the beam, the fraction of the power as a function of the far-field diffraction angle, is shown in Fig. 7. The aperture size, D, is defined as the width of the fiber array. The eight-fiber array spans nine v-grooves with one v-groove unoccupied. Therefore, D is 1.5 mm x 9 = 13.5 mm. Furthermore, we assume that a beam director will be used to reshape the fiber array output into a unity aspect-ratio beam. The three curves represent the far fields for a near field of an ideal tophat in a square aperture (uniform intensity and phase), a near field the same as our experiment but with uniform phase, and the experimental data. A common measure of beam quality in high-energy laser systems is the power-in-the-bucket (PIB) vertical beam quality (VBQ) [15], which is a related to the fraction of the power within a given far-field angle compared with a reference ideal beam (the ideal tophat in this case). The power-in-the-bucket (PIB) vertical beam quality (VBQ) [15] is given by $(c/a)^{-1/2}$ (from Fig. 7) at a far-field angle of 1.22 λ/D, and for our experiment VBQ is 1.25 times the diffraction limit. The best VBQ possible given the fill factor of the near field $(b/a)^{-1/2}$ is 1.10 times diffraction limit. It should be possible to improve the beam quality by going to a larger fill factor.

The final measure of performance is the dynamic response of the phase control system. This can be characterized by the rise time of the far-field on-axis intensity when the phase control system is activated, which is shown in Fig. 8. In this experiment, the SPGD dither frequency is 300 kHz; the rise time should be inversely proportional to the dither frequency and proportional to the number of fibers. For this 8-fiber system, the rise time is 240 μs, which is clearly fast enough for robust phase control given the phase noise spectrum in Fig. 3.

4. SUMMARY

Commercial 0.5-kW fiber amplifiers have been characterized and shown to have performance useful for coherent beam combining. Eight such fiber amplifiers were coherently combined in a tiled-aperture linear-array configuration with close to ideal performance. The beam combining efficiency was 78% and the vertical beam quality was 1.25 times diffraction limited.

5. ACKNOWLEDGEMENTS

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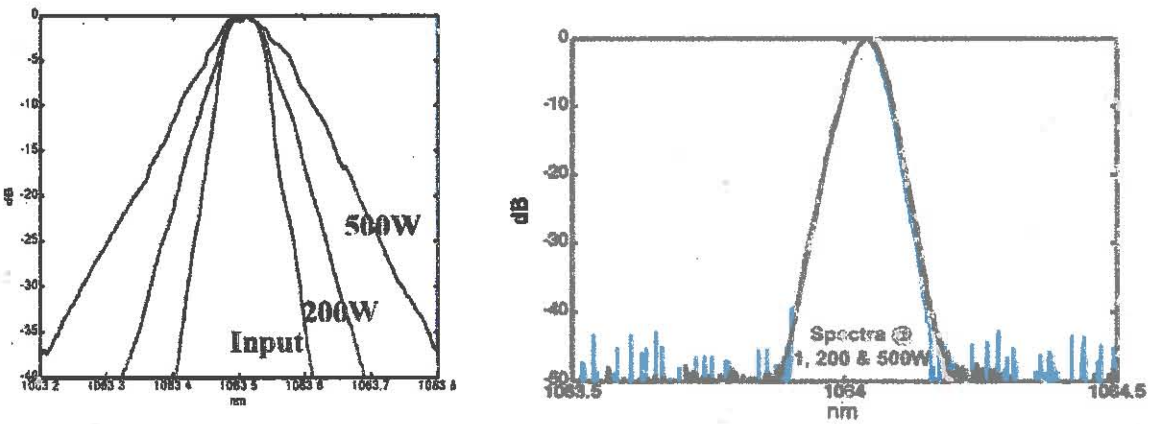

Fig. 1 Optical spectra from fiber amplifiers operating at different powers. (left) Using ASE as the input source. (right) Using phase modulated source as the input.

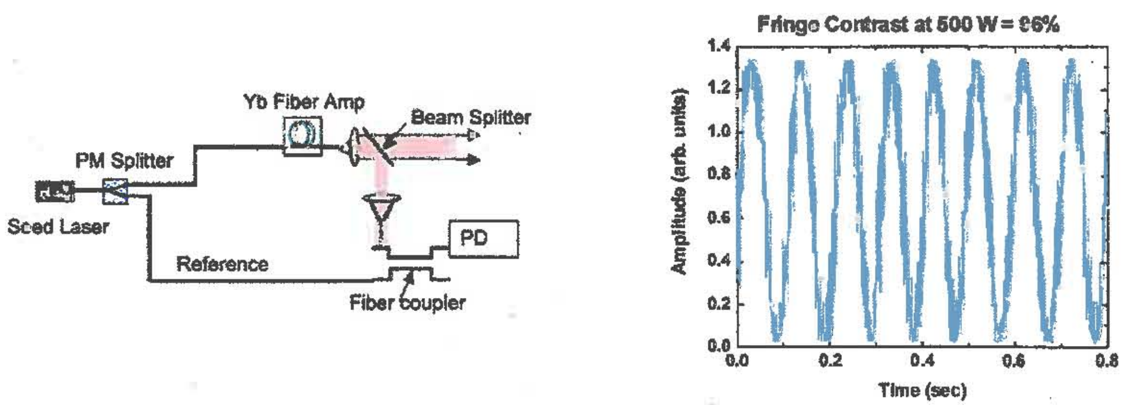

Fig. 2. Coherence measurement schematic (left) and fringe visibility from a fiber amplifier (right).

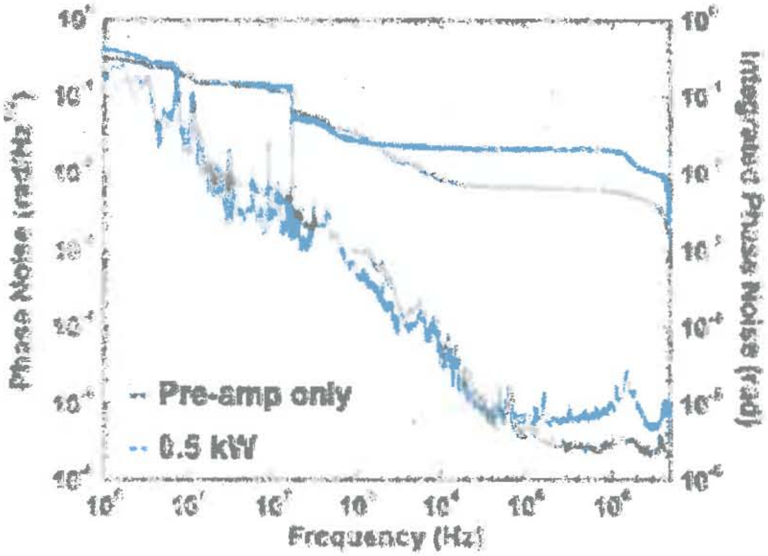

Fig. 3 Phase noise power spectral density and integrated phase noise at low power (15 W) and at full power for one of the 0.5-kW fiber amplifiers.

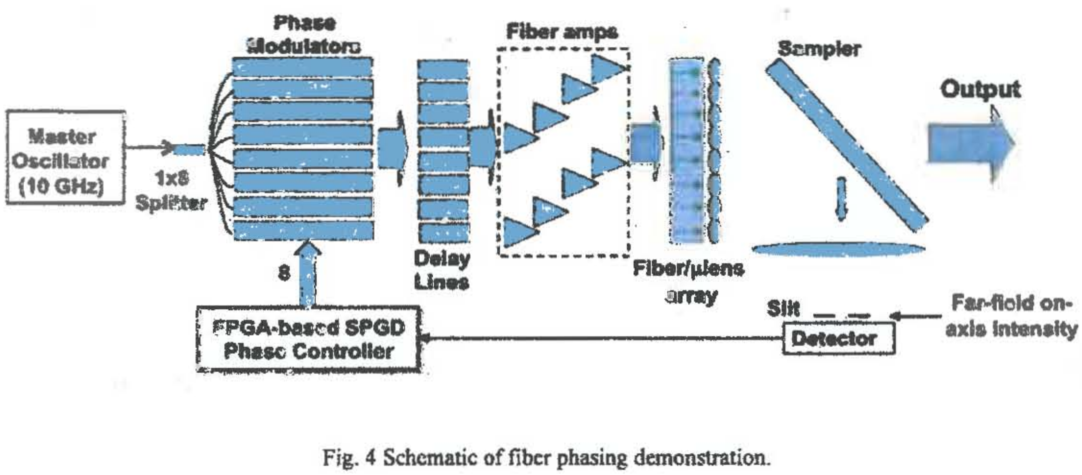

Fig. 4 Schematic of fiber phasing demonstration.

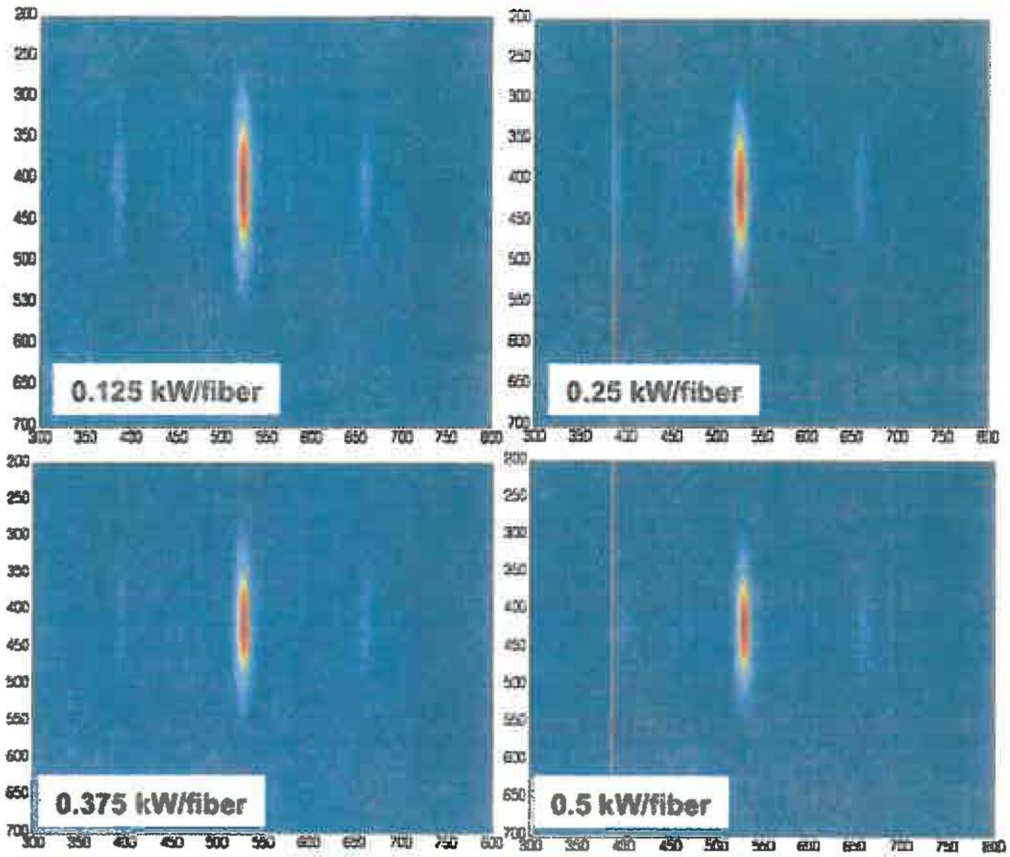

Fig 5. Far-field intensity patterns at different output powers for the 8-amplifier combined array.

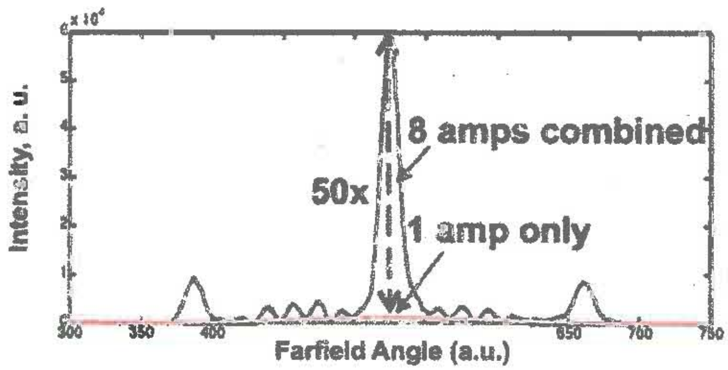

Fig. 6 Far-field intensity for a single amplifier array element and for all eight amplifier elements combined.

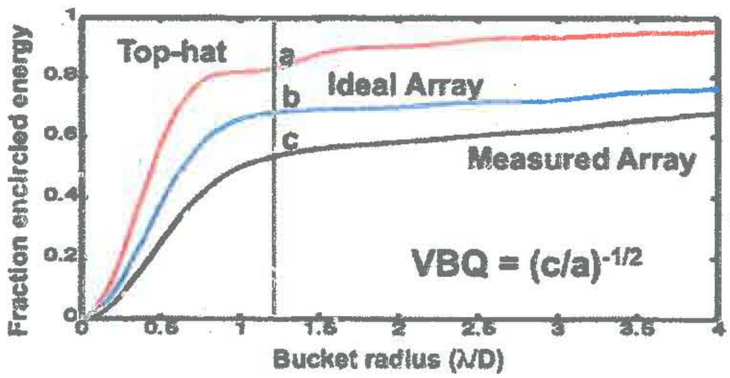

Fig. 7 Encircled far field power as a function of far-field angle, with the vertical line at 1.22 λ/D. The tophat curve is for a uniform phase and intensity beam, the ideal curve is for a uniform phase with the experimental near field pattern, and the measured array is the experimental data.

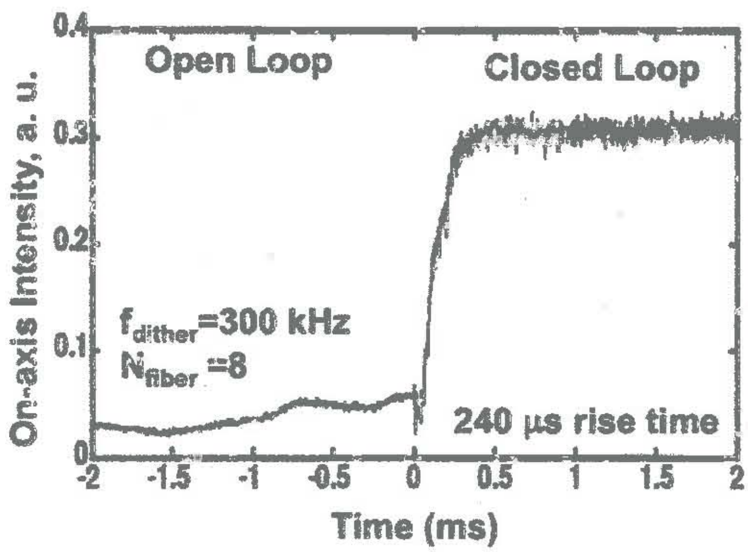

Fig. 8 The on-axis intensity as a function of time when the phase controller is engaged.

REFERENCES

[1] C. X. Yu, J. E. Kansky, S. E. J. Shaw, D. V. Murphy, and C. Higgs, "Coherent beam combining of large number of PM fibers in a 2-D fiber array," *Electron. Lett.*, vol. 42, pp. 1024-1025, 2006.

[2] S. J. Augst, T. Y. Fan, and A. Sanchez, "Coherent beam combining and phase noise measurements of ytterbium fiber amplifiers," *Opt. Lett.*, vol. 29, pp. 474-476, 2004.

[3] T. Y. Fan, "Laser beam combining for high power, high radiance sources," *IEEE J. Quantum Electron.*, vol. 11, pp. 567-577, 2005.

[4] T. M. Shay, "Theory of electronically phased coherent beam combination without a reference beam," *Opt. Exp.*, vol. 14, pp.12188-12195, 2006.

[5] J. Anderegg, S. Brosnan, E. Cheung, P. Epp, D. Hammons, H. Komine, M. Weber, and M. Wickham, "Coherently coupled high power fiber arrays," *Proc. SPIE,* vol. 6102, pp. 61020U1-5, 2006.

[6] J. Kansky, C. X. Yu, D. Murphy, S. Shaw, R. Lawrence and C. Higgs, "Beam control of a 2D polarization maintaining fiber optic phased array with high-fiber count," *Proc. SPIE*, Vol. 6306, pp. 63060G, 2006.

[7] S. J. Augst, J. Ranka, T. Y. Fan, and A. Sanchez, "Beam combining of ytterbium fiber amplifiers," *J. Opt. Soc. Am. B*, vol. 24, pp. 1707-1715, 2007.

[8] Y. Yeong, J. K. Sahu, D. Payne, and J. Nilsson, "Ytterbium-doped large-core fiber laser with 1.36 kW cw output power," *Opt. Exp.*, vol. 12, pp. 6088-6092, 2004.

[9] G. D. Goodno, S. J. McNaught, J. E. Rothenberg, T. S. McComb, P. A. Thielen, M. G. Wickham, and M. E. Weber, "Active phase and polarization locking of a 1.4 kW fiber amplifier," Opt. Lett. **35**, 1542, 2010.

[10] A. Hadjifotiou and G. A. Hill, "Suppression of stimulated Brillouin backscattering by PSK modulation for high-Power optical transmission," *IEE Proceedings*, vol. 133, pt. J, No. 4, 1986.

[11] I. Dajani, C. Zeringue, T. J. Bronder, T. Shay, A. Gavrielides and C. Robin, "A theoretical treatment of two approaches to SBS mitigation with two-tone amplification," *Opt. Exp.*, vol. 16, pp. 14233-14247, 2008.

[12] D. C. Jones, C. Stacey, and A. M. Scott, "Phase stabilization of a large-mode-area ytterbium-doped fiber amplifier," *Opt. Lett.*, vol. 32, pp. 466-468, 2007.

[13] M. A. Vorontsov and V. P. Sivokon, "Stochastic parallel-gradient-descent technique for high-resolution wave-front phase-distortion correction," *J. Opt. Soc. Am. A*, vol. 15, pp. 2745-2753, 1998.

[14] T. Y. Fan, "The effect of amplitude (power) variations on beam-combining efficiency for phased arrays," IEEE J. Sel. Top. Quantum Electron. **15**, 291-293 (2009).

[15] J. M. Slater and B. Edwards, "Characterization of high-power lasers," *Proc. SPIE*, vol. 7686, paper 76860W-12.