

Efficient coherent addition of fiber lasers in free space

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An efficient technique in which fiber lasers are coherently added in free space is presented. Since the high power of the combined output light propagates in free space rather than inside, fiber optical damage and deleterious nonlinear effects are substantially reduced. Two different configurations are investigated. One involves conventional intracavity coupling between the lasers. The other is a novel configuration where the coupling is done out of the combined cavities. The latter configuration requires much less coupling for obtaining the same output power, so the damage to the fiber is further reduced. © 2007 Optical Society of America

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Coherent addition of several low-power lasers, each with good beam quality, can lead to a laser source of high brightness.^{1–5} This is particularly suitable for fiber lasers, where fiber damage and nonlinearities can limit the power that emerges from a single fiber laser.⁶ A convenient approach for coherent addition of fiber lasers exploits intracavity fiber couplers, where all the light propagates inside the fibers and fiber couplers, thereby easing the alignment and improving the stability.^{7–9} Unfortunately, the combined output power is still limited because of damage to the core of the output fiber.

In this Letter we present a technique in which intracavity and outer-cavity coherent addition are performed in free space rather than within a fiber coupler. Accordingly, the combined output beam with its high power no longer propagates inside the fiber, so fiber damage and deleterious nonlinear effects are significantly reduced. Moreover, we develop coherent addition configurations in which the inherent light that must be coupled back into each individual fiber laser is extremely small, to reduce damage and improve the tolerance of alignments, drift, and vibrations.

We consider two free-space coherent addition Vernier–Michelson configurations¹⁰ of end-pumped fiber lasers, shown schematically in Fig. 1. The first, shown in Fig. 1(a), is an intracavity configuration. One end of each fiber is attached to a high-reflection fiber Bragg grating (FBG), and the other fiber ends are cleaved at an angle of 8° to suppress any reflections back into the fiber cores so that each fiber is essentially an amplifier. The light emerging from both fiber lasers is coherently added in free space by a 50% beam splitter and a common output coupler with 4% reflection. This configuration is analogous to the intrafiber configurations,⁴ except that the combined beam now propagates only in free space.

The second configuration, shown in Fig. 1(b), is an outer-cavity configuration. One end of each fiber is again attached to a FBG, but the other fiber end is now cleaved at 0°, which reflect 4% of the light back into the fiber core, so that each fiber behaves as an independent fiber laser resonator. The light emerging

from each fiber laser is coherently added in free space by the same beam splitter and output coupler as in the first configuration. In both configurations phase locking of the lasers results in constructive interference toward the output channel direction and destructive interference toward the loss channel direction. However, as presented below, the amount of reflection from the output coupler required for efficient lasing is much smaller for the second configuration. We also investigated the spectral characterizations of both configurations and showed that the

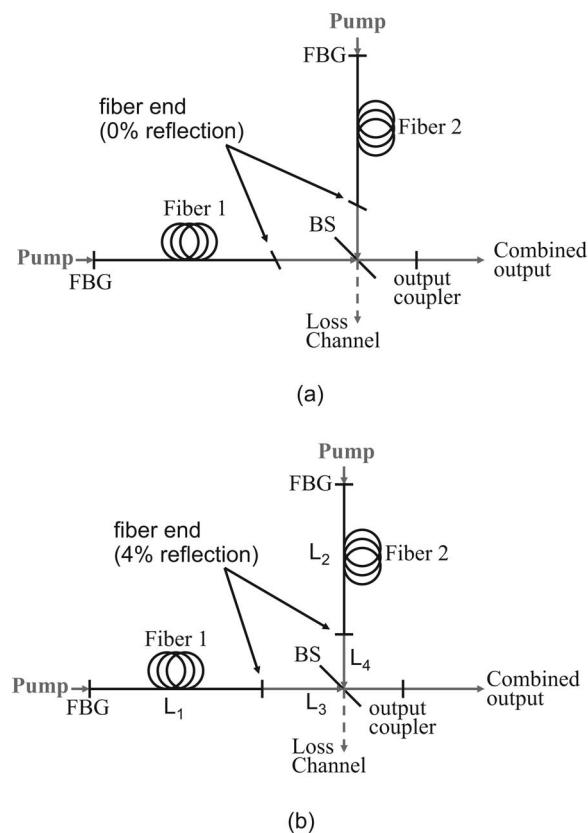


Fig. 1. Basic configurations for coherent addition of fiber lasers: (a) intracavity addition, (b) outer-cavity addition. FBG, high-reflection fiber Bragg grating; BS, 50% beam splitter.

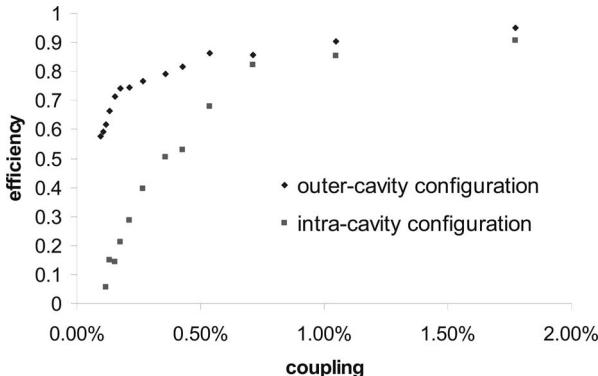


Fig. 2. Efficiency as a function of coupling for intracavity and outer-cavity configurations.

measured results agree with a simple theoretical model based on the cold-cavity effective reflectivity.¹¹

First, to obtain accurate and calibrated control of the coupling between the fiber lasers over a wide range, we added a lens in front of the 4% reflecting output coupler in both configurations. Maximum coupling is obtained when the output coupler is placed at the focal plane of the lens so that most of the reflected light will propagate exactly back into each fiber. The coupling is reduced in a well-controlled manner by displacing the output coupler from the focal plane, i.e., defocusing the light incident on the output coupler. We measured the output power as a function of the output coupler position for a single fiber laser that is 8° cleaved. The output power ranged from 300 mW at maximal coupling to 0 for the weakest coupling, confirming that the residual reflections from the 8° cleave are indeed very small. Comparing these results with those from a power model for low-reflectivity high-gain lasers¹¹ we calibrated the coupling at any position of the output coupler. We confirmed that this coupling agrees with that calculated from the overlap integral between the fiber mode (approximated as a Gaussian) and the reflected defocused Gaussian with no fitting parameters. We also measured the output power as a function of the output coupler position for a single fiber laser where one end was cleaved at 0°. This was done without the beam splitter. We determined that the output power was about $300 \text{ mW} \pm 5\%$, regardless of output coupler position.

Next, we used this calibration to measure the combined output power as a function of the coupling in both configurations. The results are presented in Fig. 2, where 1 denotes 100% efficiency and corresponds to twice the output power of a single-fiber laser, measured without the beam splitter. As is evident, even at coupling as low as 1%, 90% efficiency is obtained for both configurations (higher efficiencies, exceeding 95%, were obtained without the additional lenses). Thus, only a small amount of light needs to be reflected back into the fibers, so the risk of optical damage is low. At low coupling, the outer-cavity configuration is much more efficient than the intracavity one. For example, in the intracavity configuration combined output power reduces to 75% for coupling of 0.6%, while in the outer-cavity configuration the coupling can be low as 0.2% for the same output

power. Such a large difference is due to the fact that the coupling effects are different for the two configurations. In the outer-cavity configuration, reducing coupling keeps the power of each laser nearly unchanged and only decreases the efficiency of coherent addition of the two lasers. However, in the intracavity configuration, reducing the coupling decreases the power of each fiber laser, long before the reduction of the efficiency of coherent addition occurs.

We performed comprehensive spectral characterization for the two configurations. The simpler intracavity configuration contains only two coupled cavities with lengths L_1+L_3 and L_2+L_4 . The outer-cavity configuration contains four coupled cavities with lengths L_1 , L_2 , L_3 , and L_4 . In our experiment $L_1 = 11.62 \text{ m}$ and $L_2 = 11.02 \text{ m}$ are the optical lengths of the two fibers and $L_{3,4} \approx 0.11 \text{ m}$ are the distances from the two fiber ends to the common output coupler, while $L_4 - L_3 = 0.0048 \text{ m}$, the difference between these lengths, was very accurately controlled with a micrometer translation stage. Accordingly, the spectral separations between the longitudinal modes and the different frequency bands for the outer-cavity configuration should be $\Delta\omega_1 = c/(L_1+L_2) = 13.2 \text{ MHz}$, $\Delta\omega_2 = c/(2L_3) = 254 \text{ MHz}$, $\Delta\omega_3 = c/(2(L_1-L_2)) = 1.37 \text{ GHz}$, and $\Delta\omega_4 = c/(2(L_4-L_3)) = 50 \text{ GHz}$. We measured the overall spectrum from 1 MHz to 200 GHz of the outer-cavity configuration using a fast photodetector with a resolution of several kHz over a range of 20 GHz and an optical grating spectrometer with a resolution of 20 GHz over a range of 400 GHz. The results for the outer-cavity configuration are presented in Fig. 3. As is evident, they contain the spectral hierarchy expected for the four coupled cavities. Similar measurements for the intracavity configuration showed that only two frequency bands are present, as expected for two coupled cavities. More common longitudinal modes are seen to exist for the intracavity configuration because of fewer spectral restrictions. In general, the results show that in either configuration there are

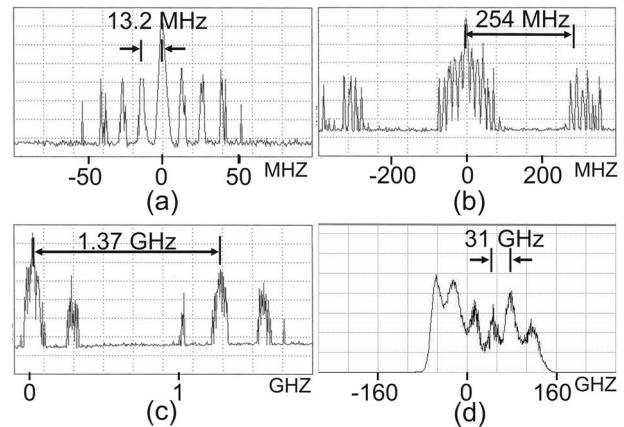


Fig. 3. Experimental overall spectrum for the outer-cavity configuration of Fig. 1(b): (a) separation between longitudinal modes, (b)–(d) separation between spectral bands. (a)–(c) were measured by Fourier-transforming the time signal of the fast photodetector and (d) with the grating spectrometer.

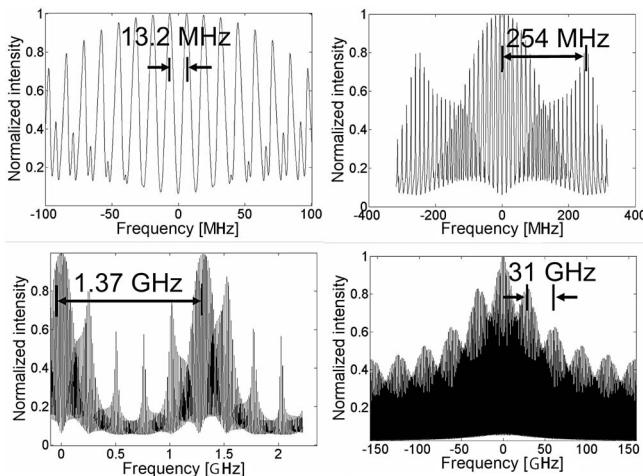


Fig. 4. Calculated overall spectrum for the outer-cavity configuration using the cold-cavity effective reflectivity. The various parts correspond to the parts in Fig. 3.

enough common longitudinal modes for efficient coherent addition.

Finally, we calculated the cold-cavity effective reflectivity, defined as the ratio between a virtual weak inserted field and the field circulating inside the cavity,¹¹ for our outer-cavity configuration. The results are presented in Fig. 4. Comparing these results with the results of Fig. 3 reveals good agreement between the experimental and the calculated spectra, indicating that the cold-cavity effective reflectivity model can indeed explain the spectral properties of our configurations. The somewhat larger number of longitudinal modes within each frequency band in the calculated spectra is due to the fact that, in a cold-cavity calculation, mode competition is absent.¹² The effective reflectivity calculations for the intracavity configuration were similarly found to be in good agreement with our measurements.

To conclude, we investigated an intracavity and an outer-cavity configuration for efficient coherent addition of fiber lasers in free space. The intracavity configuration requires at least 1% coupling for efficient coherent addition, whereas for the outer-cavity configuration the coupling can be low as 0.3%. This reduction of coupling further decreases the risk for damage at high-power operation. Although the outer-cavity configuration has a more complex spectrum, there are still many common longitudinal modes. This suggests that it should be possible to upscale the number of fiber lasers for coherent addition.

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References

1. D. Sabourdy, V. Kermene, A. Desfarges-Berthelemot, M. Vampouille, and A. Barthelemy, *Appl. Phys. B* **75**, 503 (2002).
2. L. Fabiny, P. Colet, R. Roy, and D. Lenstra, *Phys. Rev. A* **47**, 4287 (1993).
3. A. A. Ishaaya, V. Eckhouse, L. Shimshi, N. Davidson, and A. A. Friesem, *Opt. Lett.* **30**, 1770 (2005).
4. H. Bruesselback, D. C. Jones, M. S. Mangir, M. Minden, and J. L. Rogers, *Opt. Lett.* **30**, 1339 (2005).
5. V. Eckhouse, A. A. Ishaaya, L. Shimshi, N. Davidson, and A. A. Friesem, *Opt. Lett.* **31**, 350 (2006).
6. X. Zhu and R. Jain, *Opt. Lett.* **32**, 26 (2007).
7. D. Sabourdy, V. Kermene, A. Desfarges-Berthelemot, L. Lefort, and A. Barthelemy, *Opt. Express* **11**, 87 (2003).
8. D. Sabourdy, V. Kermene, A. Desfarges-Berthelemot, L. Lefort, A. Barthelemy, P. Even, and D. Pureur, *Opt. Express* **11**, 87 (2002).
9. A. Shirakawa, T. Saitou, T. Sekiguchi, and K.-i. Ueda, *Opt. Express* **10**, 1167 (2002).
10. M. DiDomenico, Jr., *Appl. Phys. Lett.* **8**, 20 (1966).
11. A. E. Siegman, *Lasers* (University Science, 1986).
12. M. C. Amann and J. Buus, *Tunable Laser Diodes* (Artech House, 1998).