CHIN. PHYS. LETT. Vol. 27, No. 12 (2010) 124201

Coherent Beam Combining of Two Fiber Amplifiers Seeded by Multi-Wavelength Fiber Laser *

WANG Xiao-Lin(王小林)**, ZHOU Pu(周朴), MA Yan-Xing(马阎星), MA Hao-Tong(马浩统), XU Xiao-Jun(许晓军), LIU Ze-Jin(刘泽金), ZHAO Yi-Jun(赵伊君)

College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073

(Received 9 February 2010)

Multi-wavelength seed laser can mitigate stimulated Brillouin scattering (SBS) and improve the output power of the narrow-linewidth fiber amplifier. In this present study, coherent combining of two fiber amplifiers seeded by a multi-wavelength laser is proposed and demonstrated using stochastic parallel gradient descent (SPGD) algorithm. The long-exposure visibility of the far field interference pattern is increased from 0.15 to 0.97 when the system evolves from open-loop to closed-loop. The feasibility of coherent combining of fiber amplifiers seeded by multi-wavelength seed laser is validated.

PACS: 42. 25. Kb, 42. 55. Wd, 42. 60. Da DOI: 10.1088/0256-307X/27/12/124201

Coherent beam combining (CBC) of fiber lasers is an efficient way to scale up high power laser with good beam quality as the power scaling of the fiber laser is restricted in terms of thermal load, fiber damage and nonlinear effect.[1] There are two main configurations of coherent beam combining, passive phasing.[2−5] and active phasing configuration.[6−13] Master oscillator power amplifier (MOPA) configuration with active phase control is the most effective way for coherent beam combination.[10,12] Up to now, the highest power demonstration of coherent beam combining has involved active phasing in MOPA configuration.[14] In active phasing MOPA configuration, single frequency seed laser is often considered to be indispensable to improve the spatial coherence property and obtain high brightness in the far-field.[15,16] Nevertheless, the maximal output power of the single frequency amplifier at 1 μm is 502 watts due to nonlinear effects, especially the stimulated Brillouin scattering (SBS) up to now,[17] which is a great challenge to scale up the total power of coherent beam combining. Multi-wavelength seed laser can mitigate SBS and improve the output power of the fiber amplifier.[16,18−20] Coherent beam combining of high power multi-wavelength lasers/amplifiers will significantly improve the total output power. It had been demonstrated that two-tone fiber amplifiers can be efficiently coherent combined using a stochastic parallel gradient descent (SPGD) algorithm.[16] Nevertheless, the two-tone seed laser is obtained by coupling two independent single-frequency fiber-pigtailed lasers. When scaled to multiple laser wavelengths, more independent single-frequency seed lasers with different central wavelength are required, which makes the whole system rather complicated, bulk and costly. In this way, if the seed laser is replaced by a single fiber laser with multiple wavelength output, the system will become considerable compact. To the best of our knowledge, the feasibility of coherent beam combining of fiber amplifiers seeded by multi-wavelength fiber laser is not reported yet. In this paper, we will propose coherent combining of two fiber amplifiers seeded by multi-wavelength laser. Experimental demonstration is implemented by coherent combining of two fiber amplifiers seeded three-tone seed laser using stochastic parallel gradient descent (SPGD) algorithm. It is to be noted that the purpose of this manuscript is not to scale laser power to an extremely high value but to demonstrate that multi-wavelength fiber laser can be an efficient seed laser source for coherent beam combining in MOPA configuration.

The experimental setup of coherent beam combining of two fiber amplifiers seeded by multi-wavelength fiber laser is shown in Fig. 1. The seed laser is a multi-wavelength seed laser. The configuration is also enclosed in Fig. 1. The laser consists of gain section (a 3 m-long Yb^{3+} doped fiber YbF pumped with 976 nm laser diode LD using wavelength division multiplexer WDM), optical isolator (ISO, it guarantees unidirectional operation), polarization controller (PC1), Sagnac loop filter (play the role of comb-like filter), phase modulator (PM, driven by a signal generator FG), and output coupler (C2, 20/80 fiber coupler, with which 20% power is extracted from the cavity and 80% power is feed back into the laser). The fiber Sagnac loop filter is formed by a 3 dB fiber coupler, a segment of polarization-maintaining fiber (PMF) and a polarization controller (PC2). With the PMF, a periodic comb filter with peak spacing given as $\Delta\lambda = \lambda^2/(\Delta nL)$ is generated, where Δn and L are birefringence and length of the PMF respectively.[21] Farthermore, by adjusting the PC2 in the Sagnac loop, the transmission ratio of the comb-like filter will change from 0 to the maximal value and the selection of wavelength number can be achieved.[22] The phase modulator driven by a signal generator (FG)

*Supported by the Innovation Foundation for Graduates in National University of Defense Technology, China under Grant No B080702.

**Email: wxllin@nudt.edu.cn

© 2010 Chinese Physical Society and IOP Publishing Ltd

provides frequency shifting feedback for the ring laser. Frequency shifting feedback cooperate with the comb filter, multi-wavelength laser with stable operation can be realized in the ring laser.[22,23] The output of multi-wavelength laser (MWL) passes through an isolator (ISO), split into 2 beams by a polarization maintained fiber splitter (C), and then coupled into two pig-tailed $LiNbO_3$ phase modulators (PM). Each phase modulator has a half-wave voltage about 3.5 V at the wavelength of 1064 nm and a bandwidth more than 100 MHz. After phase modulators and isolators, two board-wide band fiber amplifiers are used to scale power up to about 1 W. Amplified laser beams are collimated by two pig-tailed collimators (CO). The diameter of laser beam from each collimator is 5 mm. Two collimated beams pass through 10 m propagation distance and then focused by a lens (L), the lens (L) is used to simulate the far-field pattern, a beam splitter (BS) is located immediately after the lens to sample the laser beams. An infrared camera (MicronViewer 7290A, ElectroPhysics) is used to diagnose the far-field interference pattern of transmission beam at the focus plane. A photodetector (PDA36A-EC, Thorlabs) is used to detect the optical intensity of the main-lobe from the focus plane of the reflect laser beam through a home-made pinhole with 50 μm radius. The timely changed optical intensity detected by the photodetector is defined as metric function J and will be used in stochastic parallel gradient descent (SPGD) algorithm for active phase control. Cost function J is recorded by the oscilloscope (TDS7154, Tektronix) and sent to the SPGD controller. With the SPGD algorithm, phase control signals are generated and applied on $LiNbO_3$ phase modulators (PM) by the SPGD controller, and active phase locking is implement.

By adjusting of the PC1 and PC2, stable three-wavelength output laser is achieved, the laser spectrum is measured by an optical spectrum analyzer (Agilent 86140B), shown in Fig. 2(a). The peak spacing is about 2 nm, among each laser line the amplitude difference is less than 3 dB. After the power amplification, the spectrum is shown in Fig. 2(b), it is shown that the amplified spontaneous emission (ASE) is suppressed by 30 dB.

The visibility of for coherent beam combining of two channel multi-wavelength laser can be described as [24]

$$V = \left| \frac{\sin(\frac{N\pi dv\Delta l}{c})}{N\sin(\frac{\pi dv\Delta l}{c})} \right|, \qquad (1)$$

where N is the number of the wavelength, $d\nu$ is the frequency difference between each wavelength, Δl is the optic path difference between the two lasers. The visibility is defined by the formula $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, $I_{\max}$ and $I_{\min}$ are the maximum intensity and the adjacent minimum of the intensity pattern, respectively.

As the visibility is a periodic function of optics path difference Δl, in order to realize high visibility interference pattern, two step optical path and phase control should be carried out. First, optical path difference is roughly tuned to ensure the high visibility interference pattern can be obtained. In our experiment, the optical path difference is controlled by cutting and fusion of the fibers and tuning of the optical path of each laser beams in the free space. Then, precisely phase control against the phase noise is implemented by the phase modulator using SPGD algorithm.

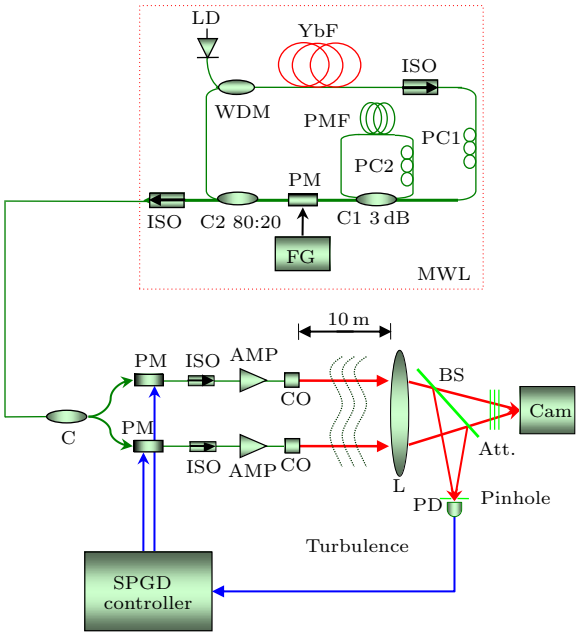


Fig. 1. Experimental setup of coherent beam combining of two amplifiers seeded by a single multi-wavelength laser. YbF:Yb^{3+} doped fiber. WDM: wavelength division multiplexer, LD: laser diode, ISO: isolator, PC1, PC2: polarization controller, PMF: polarization-maintaining fiber, C, C1, C2: fiber coupler. PM: phase modulator, FG: function generator, CO: Collimator. L: Lens, Att: Attenuators, Cam: infrared camera. PD: photo detector. MWL: multi-wavelength laser (in the dashed-enclosed frame).

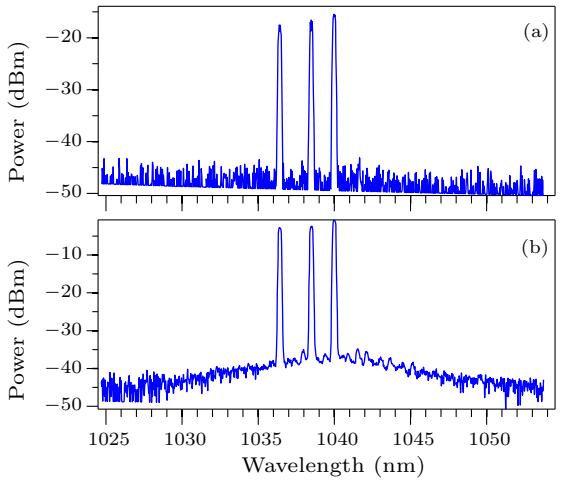


Fig. 2. Multi-wavelength laser operations before (a) and after (b) fiber amplifier.

The steps for SPGD algorithm can be briefly de-

scribed as follows.[25–27] Metric function $J = J(\boldsymbol{u})$ is a function of $\boldsymbol{u}$, where $\boldsymbol{u} = (u_1, \cdots, u_j, \cdots, u_N)$, u_j is control signal applied to the $LiNbO_3$ phase modulator. The algorithm is implemented in infinite iterations until ended manually. Each iteration cycle works as follows.

(1) Generate statistically independent random perturbations $\delta\boldsymbol{u} = \{\delta u_1, \delta u_j, \cdots, \delta u_N\}$. Here $\langle \delta u_k \rangle = 0$ and $\langle \delta u_k \delta u_l \rangle = \sigma^2 \delta_{kl}$, δ_{kl} is the Kronecker symbol and σ is a disturbance variable.

(2) Apply the positive $(\boldsymbol{u} + \delta\boldsymbol{u})$ and negative $(\boldsymbol{u} + \delta\boldsymbol{u})$ perturbations and obtain the cost function $J^+ = J(\boldsymbol{u} + \delta\boldsymbol{u})$ and $J^- = J(\boldsymbol{u} - \delta\boldsymbol{u})$ successively.

(3) Compute difference of the metric function using $\delta J = J^+ - J^-$, then update the control voltages $u_i = u_i + \gamma \delta u_i \delta J$, where γ is the update gain, $\gamma > 0$ accords to the procedure of maximization in the coherent beam combining.

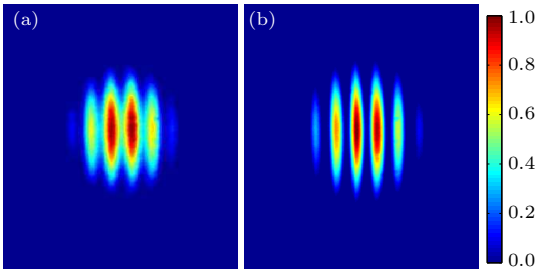


Fig. 3. Long exposure far field interference patterns in open-loop (a) and close-loop (b).

In the absence of the active phase control, partially coherent far field interference pattern is obtained as shown in Fig. 3(a). The intensity distribution of the profile along transverse direction indicates a visibility of 0.15, which is a partially coherent pattern. With the SPGD controller, long time stable coherent combining of two beams are demonstrated in three-tone operations. An in-phase interference pattern with the visibility of 0.975 is obtained when the SPGD algorithm is implemented, as shown in Fig. 3(b). The result shows that the fringe visibility is increased from 0.15 to 0.97. The power encircled in the main-lobe is 0.72 times of increase when the system evolves from open-loop to close-loop, which is 97% of the ideal coherent combining state.

In summary, we have demonstrated coherent beam combining of two fiber amplifiers with a single multi-wavelength seed laser. A stable three-wavelength laser is built and then amplified by two fiber amplifiers. Active phase control on each fiber amplifier is implemented using stochastic parallel gradient descent (SPGD) algorithm. Note that multi-tone seed laser can mitigate SBS and improve the output power of the fiber laser amplifier,[16,18–20] multi-wavelength seed laser coupled by several difference single wavelength lasers is costly and bulk, coherent combining of amplifiers seeded by a multi-wavelength seed laser in MOPA configuration provides a promising way for robust scaleable high power coherent beam combining.

References

[1] Galvanauskas A 2004 *Opt. Photon. News* **15** 42
[2] He B, Lou Q H and Zhou J 2006 *Chin. J. Laser* **33** 1153
[3] Li L, Schülzgen A, Li H, Temyanko V L, Moloney J V and Peyghambarian N 2007 *J. Opt. Soc. Am.* B **24** 1721
[4] He B, Lou Q H, Zhou J, Zheng Y H, Xue D, Dong J X, Wei Y R, Zhang F P, Qi Y F, Zhu J Q, Li J Y, Li S Y and Wang Z J 2007 *Chin. Opt. Lett.* **5** 412
[5] Wu T W, Chang W Z, Galvanauskas A and Winful H G 2009 *Opt. Express* **17** 19509
[6] Ma Y X, Liu Z J, Zhou P, Wang X L, Ma H T, Li X, Si Lei and Xu X J 2009 *Chin. Phys. Lett.* **26** 044204
[7] Zhou P, Liu Z J, Wang X L, Ma Y X, Li X, Xu X J and Guo S F 2009 *Chin. Phys. Lett.* **26** 044202
[8] Wang X L, Ma Y X, Zhou P, Ma H T, Li X, Xu X J and Liu Z J 2009 *Laser Phys.* **19** 984
[9] Zhou P, Liu Z J, Wang X L, Ma Y X, Ma H T and Xu X J 2009 *Opt. Laser Technol.* **41** 853
[10] Shay T M, Benham V, Bake J T, Sanchez A D, Pilkington D and Lu A C A 2007 *IEEE J. Sel. Top. Quantum Electron.* **13** 480
[11] Kansky J E, Yu C X, Murphy D V, Shaw S E J, Lawrence R C and Higgs C 2006 *Proc. SPIE* **6306** 63060G
[12] Anderegg J, Brosnan S, Cheung E, Epp P, Hammons D, Komine H, Weber M and Wickham M 2006 *Proc. SPIE* **6102** 61020U
[13] Liu L, Vorontsov M A, Polnau E P et al 2007 *Proc. SPIE* **6708** 67080K
[14] Grumman 2009 *Northrop Grumman Scales New Heights in Electric Laser Power, Achieves 100 Kilowatts From a Solid-State Laser*, http://www.irconnect.com/noc/press/pages/news_releases.html?d=161575
[15] Limpert J, Röser F, Klingebiel S, Schreiber T, Wirth C, Peschel T, Eberhardt R, Tünnermann A, Tünnermann 2007 *IEEE J. Sel. Top. Quantum Electron.* **13** 537
[16] Zhou P, Ma Y X, Wang X L, Ma H T, Xu X J and Liu Z J 2009 *Opt. Lett.* **34** 2939
[17] Gray S, Liu A, Walton D T, Wang J, Li M, Chen X, Boh A R, Demeritt J A and Zenteno L A 2007 *Opt. Express* **15** 17044
[18] Dajani I, Zeringue C and Shay T 2009 *IEEE J. Sel. Top. Quantum Electron.* **15** 406
[19] Weßels P, Ade P, Auerbach M, Wandt D and Fallnich C 2004 *Opt. Express* **12** 4443
[20] Dajani I, Zeringue C, Bronder T J, Shay T, Gavrielides A and Robin C 2008 *Opt. Express* **16** 14233
[21] Zhang Z X, Wu J, Xu K, Hong X B and Lin J T 2009 *Opt. Express* **17** 17200
[22] Bellemare A, Karasek M and Rochette M 2000 *IEEE J. Lightwave Technol.* **18** 825
[23] Slavík R and Larochelle S 2002 *Opt. Lett.* **27** 28
[24] Koechner W 2005 *Solid-state Laser Engineering* 6th edn (New York: Springer)
[25] Carhart G W, Ricklin J C, Sivokon V P and Vorontsov M A 1997 *Proc. SPIE* **3126** 221
[26] Vorontsov M A and Carhart G W 1997 *Opt. Lett.* **22** 907
[27] Vorontsov M A, Carhart G W, Cohen M and Cauwenberghs G 2000 *J. Opt. Soc. Am.* A **17** 1440