Coherent beam combining of hybrid phase control in master oscillator-power amplifier configuration*

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(Received 18 January 2010; revised manuscript received 8 February 2010)

A novel scalable architecture for coherent beam combining with hybrid phase control involving passive phasing and active phasing in master oscillator-power amplifier configuration is presented. Wide-linewidth mutually injected passive phasing fibre laser arrays serve as master oscillators for the power amplifiers, and the active phasing using stochastic parallel gradient descent algorithm is induced. Wide-linewidth seed laser can suppress the stimulated Brillouin scattering effectively and improve the output power of the fibre laser amplifier, while hybrid phase control provides a robust way for in-phase mode coherent beam combining simultaneously. Experiment is performed by active phasing fibre laser amplifiers with passive phasing fibre ring laser array seed lasers. Power encircled in the main-lobe increases1.57 times and long-exposure fringe contrast is obtained to be 78% when the system evolves from passive phasing to hybrid phasing.

Keywords: fibre laser, coherent beam combining, hybrid phase control, stochastic parallel gradient descent algorithm

PACC: 4225K, 4255N, 4290

1. Introduction

Coherent beam combining (CBC) of fibre lasers/amplifiers is an efficient way to scale up the output power with good beam quality as the fibre laser power scaling is restricted by thermal load, fibre damage and nonlinear effect.[1] There are two types of coherent beam combining: passive phasing[2−7] and active phasing in master oscillator and power amplifier (MOPA) configuration.[8−14] The passive phasing, including multi-core fibre laser,[2] self-organised laser array,[3,4] self-imaging confocal resonator,[5,6] holds the advantages of compact bulk and is rid of complex active phase detection and control technology. Nevertheless, stable in-phase mode of coherent laser array is hard to achieve unless special countermeasures are taken to insulate environment perturbations. In general environment conditions, in-phase mode is reached intermittently and the results are not consistently repeatable.[7,15] While the active phasing in MOPA configuration is an effective way of realizing the stable in-phase mode coherent beam combining.[9,11] Up to now, the highest power demonstrations of coherent beam combining have involved active phasing in MOPA configuration.[16] In the active phasing MOPA configuration, signal frequency seed laser is often considered to be necessary to improve the spatial coherence property and obtain high brightness in the far-field.[17] So far, the output power of the single frequency amplifier has reached the level of about hundreds of watts as it is restricted by nonlinear effects, especially the stimulated Brillouin scattering (SBS).[18−20] While in the passive phasing configuration, the spatial coherence property can be well maintained when temporal coherence is seriously degraded with laser wavelength spreading over a range of several nanometers,[21] in which case the SBS can be effectively suppressed.

In this paper, a novel scalable coherent beam combining architecture with hybrid phase control in MOPA configuration is presented. Power amplifiers seed by wide-linewidth self-organised fibre laser array, therefore the passive phasing is established by multi-injection. Phase modulators are used, and active phase control can be implemented. In this configuration, hybrid phase control provides a robust way of implementing the in-phase mode coherent beam combining, while wide-linewidth seed lasers can suppress the SBS effectively and increase the output power of the fibre laser amplifier simultaneously. CBC experiment is performed with the hybrid phase control in MOPA configuration. Self-organised all fibre ring

*Project supported by the Innovation Foundation for Graduates in National University of Defense Technology, China (Grant No. B080702).

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laser array is built as seed lasers which ensure the passive phasing, and the stochastic parallel gradient descent (SPGD) algorithm is used to implement the active phase control. With this configuration, stable in-phase mode coherent beam combination is obtained in a turbulent atmosphere for a long time. Moreover, stable out-phase mode is also obtained by changing the parameters in the SPGD algorithm.

2. Experimental setup of hybrid phase control in MOPA configuration

The experimental setup is shown in Fig. 1. All components in two ring lasers are polarisation-maintained. Two mutually coupled polarisation maintaining ring lasers serve as the seed lasers for the power amplifiers. Each ring laser consists of gain section (Yb^{3+} doped fibre (YDF) pumped with 976 nm laser diode (LD) using wavelength division multiplexer (WDM)), optical isolator (ISO, it guarantees unidirectional operation), output coupler (C, 3 dB fibre coupler, with which 50% power is extracted from the cavity and 50% power is fed back into each laser), fibre Bragg grating (FBG, central wavelength is 1064 nm, reflectivity $> 99\%$, and bandwidth < 0.3 nm), and output ISO. Two lasers are mutually coupled by the common arm of a coupler: the electric field in one laser is strongly coupled to and affected by that in another laser, passive phasing in laser array is thereby built. Two $LiNbO_3$ phase modulators (PM) located behind the output isolators are used as active phasing components. Each PM has a half-wave voltage of 3.5 V at the 1064 nm wavelength. The laser beams from the PM pass through two ISO and are then sent into two power amplifiers, and laser powers can scale up to 1 W by power amplifiers. Amplified laser beams are sent into free space via two collimators (CO). The diameter of laser beam output from each collimator is 8 mm and the distance between collimators is about 12 mm. Two collimated beams pass through a 10 m propagation distance and then are focused by a lens (L), which is used to simulate the far-field pattern. In the free space, turbulences are induced by round-the-clock working cooling fans and air-conditioners in the clean-room laboratory. The focused beam array is sampled by a beam splitter (BS). One part of the beam is sent to an infrared camera (MicronViewer 7290A, Electro-Physics) to diagnose the profile of the combined beam. Another part of the beam is sent to a photodetector (PDA36A-EC, Thorlabs) via a pinhole. The photodetector is used to detect the optical intensity of the main-lobe from the focal plane. The pinhole diameter (50 μm) is less than the main-lobe width (about 120 μm) of the interference pattern. The time-varying optical intensity of the main-lobe detected by the photodetector is defined as metric function J and will be used in the SPGD algorithm based active phasing system. Metric 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 to $LiNbO_3$ PM by the SPGD controller, active phase locking is thereby established.

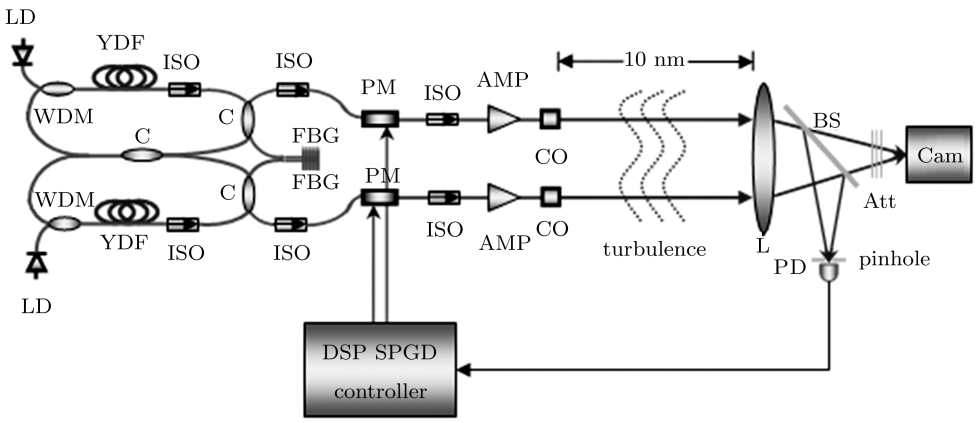


Fig. 1. Experimental setup of coherent beam combining with hybrid phase control in MOPA configuration. LD, laser diode; WDM, wavelength division multiplexers; YDF, Yb^{3+}-doped fibres; C, coupler; ISO, isolator; FBG, fibre Bragg grating; PM, phase modulator; AMP, fibre amplifier; CO, collimator; L, lens; Att, attenuators; Cam, infrared camera; PD, photodetector.

The SPGD algorithm[22−25] is used for the active phasing. The metric function $J = J(\boldsymbol{u})$ is a function of $\boldsymbol{u}$, where $\boldsymbol{u} = (u_1, \ldots, u_j, \ldots, u_N)$, u_j is control signal applied to the $LiNbO_3$ PM. Through controlling u's with the SPGD algorithm, the maximal value of J will be acquired and the coherent combining approaches to the ideal one.[26,27] The algorithm is implemented in infinite iterations until ended manually. Each iteration cycle works as follows.

(1) Generate statistically independent random perturbations and convert them to voltages $\delta\boldsymbol{u} = \{\delta u_1, \delta u_j, \ldots, \delta u_N\}$, where all $|\delta u_i|$ are small values that are typically chosen as statistically independent variables having zero mean and equal variances, i.e. $\langle \delta u_k \rangle = 0$, and $\langle \delta u_k \delta u_l \rangle = \sigma^2 \delta_{kl}$, where δ_{kl} is the Kronecker symbol and σ is the disturbance variable.

(2) Apply the control voltages to the PM with the positive perturbations and obtain the metric function from the detector $J^+ = J(\boldsymbol{u} + \delta\boldsymbol{u})$, then apply the control voltages with the negative perturbations and obtain the metric function $J^- = J(\boldsymbol{u} - \delta\boldsymbol{u})$.

(3) Estimate the grads of the metric function J with the function $\delta J = J^+ - J^-$.

(4) Update the control voltages $u_i = u_i + \gamma \delta u_i \delta J$, where γ is the update gain. $\gamma > 0$ accords with the procedure of maximisation in the coherent beam combining.

3. Results and discussion

The spectra of two coupled lasers are measured and shown in Fig. 2. The mutual injection of the lasers makes the spectra of the two lasers almost overlap with each other. The 3 dB line-width is about 0.035 nm (10.5 GHz linewidth), which is broad enough compared with the Brillouin linewidth (∼50–100 MHz).

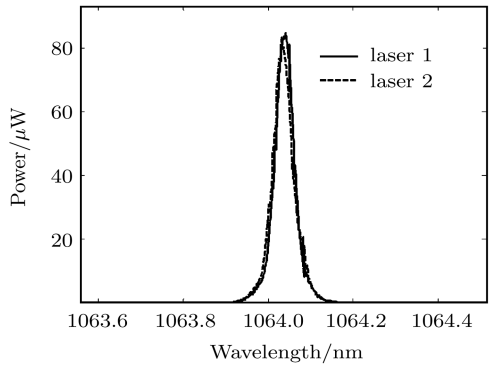


Fig. 2. Spectra of two self-organized fibre ring lasers.

In the absence of the active phase control, clear interference pattern with high visibility can be observed,[4,7] but the interference pattern keeps shifting due to phase fluctuations induced by the cooling fans, air-conditioners and shake of the cooling water tank in the clean room lab. In-phase and out-phase modes are the two main modes in the self-organised coherent beam combining in the perturbation environment.[7] The time-varying metric function J (defined as the intensity of main-lobe detected by the photodetector) evolves from only passive phasing (open-loop) to hybrid phase control (close-loop), which is shown in Fig. 3. Corresponding long-exposure interference patterns are also displayed in Fig. 3. In the absence of active phase control (the first 22.5 s), the passive phasing of the laser array plays a role of phase locking. It is found that the metric function holds almost two values: zero and maximal values, which are accordant with the in-phase and the out-phase modes of the two lasers.[7] The mean value (the line in the first 22.5 s of Fig. 3) of the metric function in an open-loop is 1.12 V. The corresponding long-exposure far-field interference pattern is almost the same as a non-coherent one because of the alternating changes of in-phase and out-phase modes. In the hybrid phase control state, we set $\sigma = 0.25$ and $\gamma = 1.0$, implement the SPGD algorithm and apply the phase control signal to the PM in the mutually coupled laser array. Long time in-phase interference pattern is obtained as shown in the last 22.5 s in Fig. 3. With the robust active phase control, the mean value (the line in the last 22.5 s of Fig. 3) of the metric function is 1.76 V in the close-loop, 1.57 times higher than of the open-loop state. Corresponding long-exposure interference pattern indicates the visibility (fringe contrast) is about 0.78, where the visibility is determined by the formula $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, $I_{\max}$ and $I_{\min}$ are the maximum intensity and the adjacent minimum intensity of the pattern respectively.

Figure 4 shows the probability distributions of the metric function with and without active phase control. The probability of energy encircled in the main-lobe larger than 70% of its ideal value is increased from 33% to 70% when the system evolves from open-loop to close-loop. Figures 3 and 4 indicate that with hybrid phase control, the stable in-phase coherent combining of the fibre laser array can be achieved in long time in turbulence atmosphere.

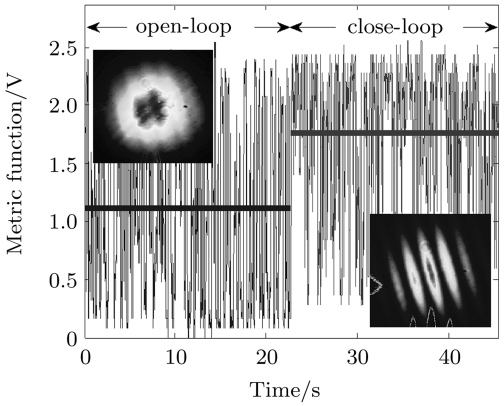


Fig. 3. Metric functions and corresponding interference patterns evolving from open-loop (without active phase control) to close-open (with active phase control).

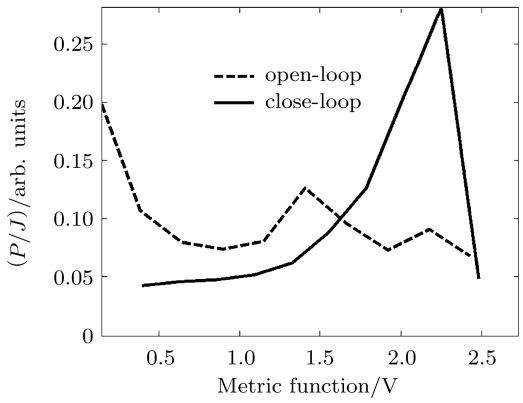


Fig. 4. Probability distributions of metric function J in open-loop and close-loop.

4. Conclusions

We demonstrate a novel scalable architecture for coherent beam combining with hybrid phase control in MOPA configuration. Robust coherent beam combining of active phasing fibre laser amplifiers seeded by passive phasing fibre ring laser array is realised in turbulence atmosphere. Despite perturbations of the environmental, the visibility increases from 0 to 0.78 and the mean intensity of the main-lobe increases 1.57 times when the system evolves from open-loop to close-loop. Wide-linewidth seed laser in passive phasing array can suppress SBS and improve the output power of the fibre laser amplifier, while hybrid phase control provides a robust way of implementing the in-phase mode coherent beam combining simultaneously. This approach combines the advantages of passive phasing and active phasing. As the scaling the configuration to a higher power involves increasing the number of laser elements and the amplifier power per channel, we believe that this approach may be a promising way for scaling to high power coherent beam combining.

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