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2 kW single-mode fiber laser employing bidirectional-pump scheme

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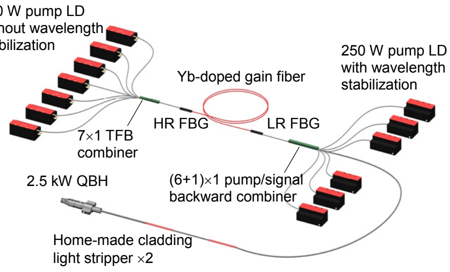

Abstract: A 2 kW single-mode fiber laser with two cascade home-made cladding light strippers (CLSs) has been demonstrated by employing bidirectional-pump scheme. 2.009 kW signal power is obtained when pump power is 2.63 kW and the slope efficiency is 76.6%. Raman Stokes light is less than -47 dB at 2.009 kW even with a 10-m delivery fiber with core/inner cladding diameter of 20 μm/400 μm. The beam quality $M^2 \leqslant 1.2$ and the spectral FWHM bandwidth is 4.34 nm. There is no transverse mode instability and the output power stability of ±0.14% is achieved by special thermal management for a more uniform temperature distribution on the Yb-doped gain fiber.

Keywords: fiber laser; high power; stimulated Raman scattering; power stability

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1 Introduction

In the last decades, high power single-mode and multi-mode fiber lasers have been used in many industry fields such as welding and cutting [1]. The output powers of fiber lasers have also increased remarkably [2−9]. But, transverse mode instability (TMI) has been found when the power scaling of the single-mode fiber lasers is above 2 kW[10-14]. The fiber nonlinear effect, especially the stimulated Raman scattering (SRS), also limits the power scaling of continue-wave single-mode fiber laser and causes the output power instability of the fiber laser. Photo-darkening (PD) is also found in Yb-doped high power fiber laser, which can cause the decrease of output power, long term stability and operation life of the fiber laser. Koponen has observed a seventh-order dependence of the PD rate on the excited-state Yb concentration for two different fibers. This result implies that PD of an Yb-doped fiber source fabricated using a particular fiber will be strongly dependent on the Yb inversion rate[15,16] and lower inversion rate can be obtained by using 976 nm pump light as compared to 915 nm. Therefore, 976 nm pump LDs are used in our fiber laser system to obtain lower inversion rate to decrease PD. Besides, a more uniform pump energy distribution at both ends of gain fiber can be realized by bidirectional pumping compare to co-pumping and it is also beneficial to obtain lower inversion rate to decrease PD.

We demonstrated a single-mode fiber laser employing bidirectional-976 nm pump scheme, and high SRS suppression and remarkable power stability are demonstrated without any TMI.

2 Experimental setup

The experimental setup of bidirectional-976 nm pumped all fiber laser is presented in Fig. 1. 250 W wavelength stabilized 976 nm laser diodes of DILAS company are used for backward-pumping and forward and backward combiners are used to combine the bidirectional-pumping light into the inner cladding of the double cladding fibers with a diameter of 400 μm and a numerical aperture of 0.46. The 7 × 1 pump combiner is adopted as the forward-pump combiner and the pump light is launched into the double-cladding fiber (DCF) through the high reflective fiber Bragg grating (HR FBG) of ITF with operating wavelength 1080.06 nm, FWHM 1.96 nm and 99.6% reflectivity. A (6 + 1) × 1 signal/pump combiner is used as the backward-pump combiner, and the backward-pump light was coupled into the OC FBG of ITF company with operating wavelength 1079.96 nm, FWHM 1.03 nm and 9.6% reflectivity. The signal fiber of

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the (6+1)×1 signal/pump combiner is DCF with a core diameter/*NA* of 20 μm/0.064, and the cladding diameters of input and output signal fiber are 400 μm and 250 μm, respectively. The gain fiber is double-cladding Yb-doped fiber (DCYDF) with a core diameter/*NA* of 20 μm/0.064. Yb-doped fiber (YDF) we have adopted has an absorption coefficient ~1.6 dB/m at 976 nm and the length is set to be ~20 m. After the backward (6 + 1) ×1 signal/pump combiner, about 10 m delivery fiber with core/inner cladding diameter of 20 μm/400 μm, is spliced, an QBH fiber optic cable of optoskand is used and two cascade homemade CLSs are adopted to strip cladding lights to get a good beam quality (M^2 <1.2). Output signal spectrum and beam quality at the maximum power are measured and recorded.

3 Results and discussion

The signal power vs. pump power (S-P) performance, beam distribution and quality, output spectrum and output power temporal characteristic of the fiber laser with bidirectional-pumping configuration were measured and recorded. The forward-pump is firstly utilized and then backward-pumping is utilized to further scale the output power of the laser oscillator. Besides, the performance of the homemade CLS used in the 2 kW system is described.

3.1 Output characteristics

Fig. 2 shows the maximum output power measured by 5000-BB-V1 of Ophir VEGA and 2.009 kW was recorded when the temperature of the cooling water was set at

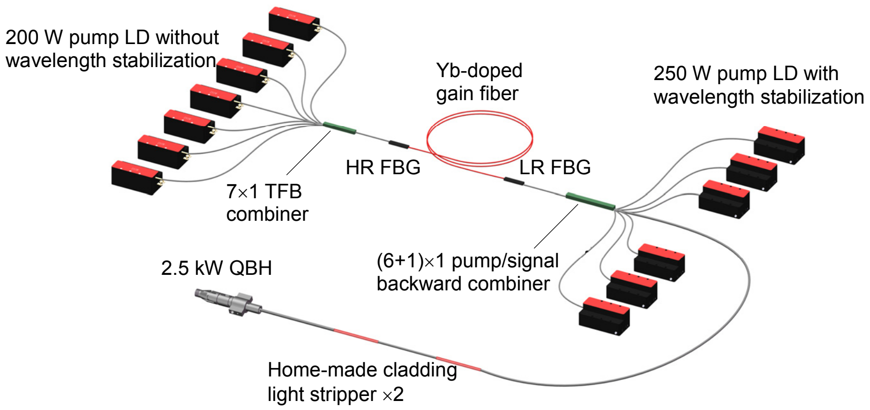

Fig. 1 Setup of bidirectional-976 nm pumped all-fiber laser.

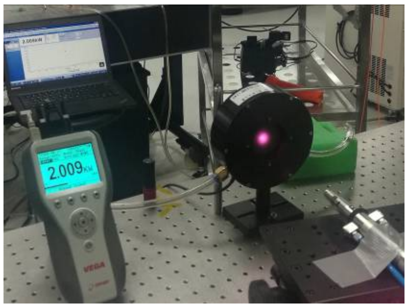

Fig. 2 Maximum output power measured by 5000-BB-V1 of Ophir VEGA.

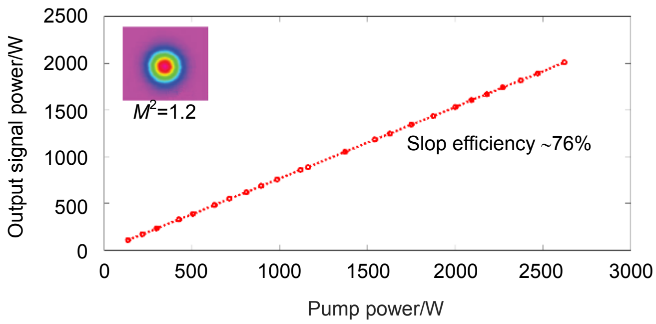

Fig. 3 Output power versus pump power, and beam profile at focal point.

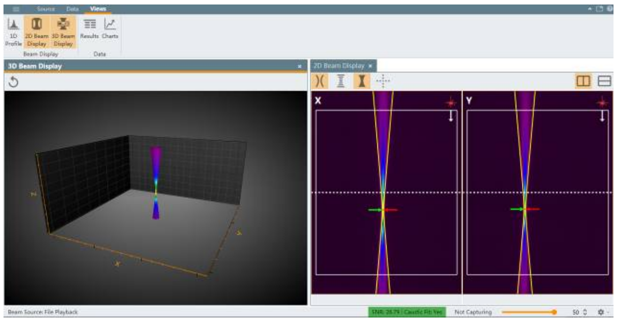

Fig. 4 2D and 3D beam display at maximum output power.

25 ℃. S-P performance is shown in Fig. 3 and a slop efficiency 76.6% is obtained at maximum output power with maximum temperature below 60 ℃. Because the forward pump LDs are non-wavelength-stability (without external volume Bragg gratings for wavelength stabilization)[17], the forward signal power is first utilized up to 928 W at current 30.5 A , and then backward-pump power is added to further scale the output power of the laser oscillator above 2 kW at current 34 A. Beam distribution and quality were measured by BeamWatch of Ophir which used to detect the above 1 kW high power fiber laser specialized. The 2D and 3D beam displays were shown in Fig. 4 and the beam quality M^2 at x and y axes are both below 1.2.

3.2 Output spectrum and temporal characteristic

Fig. 5 shows the output signal spectrum and the Raman Stokes light is less than -47 dB below the signal power at the maximum power of 2.009 kW even with a 10-m 20 μm/400 μm delivery DCF. There is no obvious residual pump power because of two cascades homemade CLSs adopted. For obtaining a good beam quality, delivery fiber with core diameter of 20 μm and *NA* 0.064 is used, and self-phase modulation (SPM) is observed when high power laser is passing along 10 m power delivery fibers. Meanwhile, the temporal characteristic at maximum output power is recorded by 5000-BB-V1 of Ophir VEGA in 5 mins as shown in Fig. 6 and ±0.14% power fluctuation is demonstrated. By using a special thermal man-

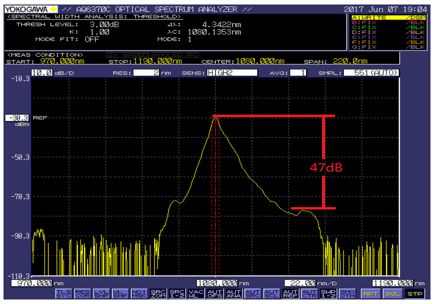

Fig. 5 Laser output spectra at the maximum output power (P=2.008 kW).

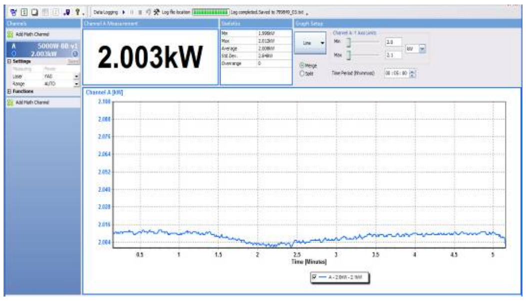

Fig. 6 Laser output temporal characteristic at the maximum output power.

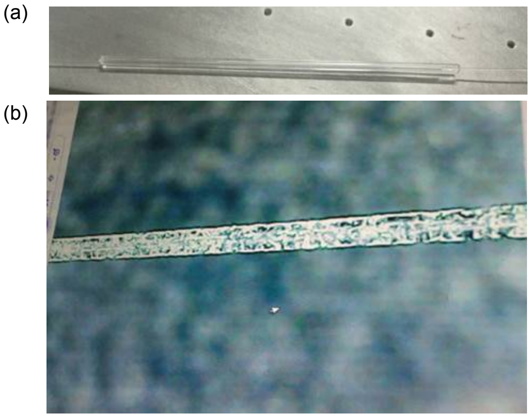

Fig. 7 (a) The picture of the encapsulated CLS. (b) The picture of the surface of CLS after abrading.

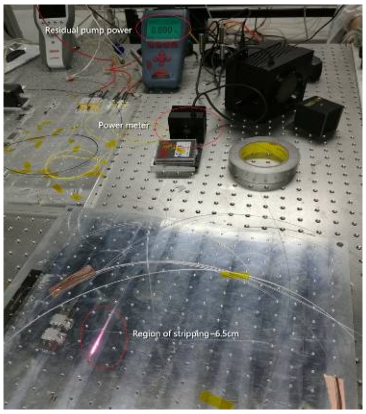

Fig. 8 Residual pump power when 209.4 W pump power goes through the homemade CLS.

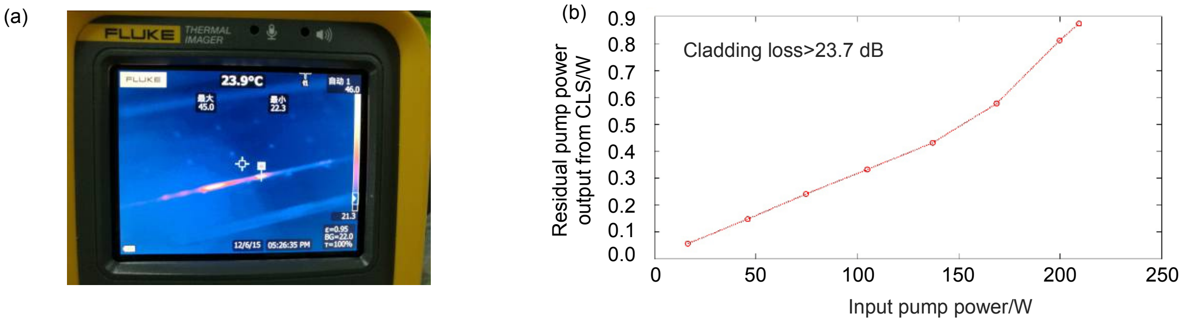

Fig. 9 (a) Temperature of CLS when 209.4 W pump power goes through. (b) Residual pump power output from the CLS vs. input pump power 209.4 W.

agement to make the temperature distribution of Yb-doped gain fiber uniform, a long term power stability can be achieved and no TMI is found in the bidirectional-pumping scheme at 2 kW.

3.3 Performance of the CLS

A homemade CLS with high cladding loss is used in the 2 kW fiber laser, which is fabricated directly on the output signal fiber with 250 μm cladding diameter of (6+1)×1 pump and signal combiner. The fiber is stripped in the middle with a length of 6.5 cm and a mechanical method and homemade equipment were used to grind and polish the bare fiber to obtain a smaller cladding and rough surface. Cladding lights leaks out because of the dissatisfaction of the total reflection condition. Figs. 7(a) and 7(b) show the picture of the encapsulated CLS and the surface of CLS after abraded. Fig. 8 shows the residual pump power when 209.4 W pump power goes through the homemade CLS without any air cooling or water cooling and the cladding loss is greater than 23.7 dB for a 6.5 cm fiber length with the temperature below 50 ℃(as shown in Fig. 9(a)). As shown in Fig. 9(a), there is an optimal fiber length for CLS and most of cladding power has been stripped during a length of about 4 cm. A 200 W single-mode 1 μm all-fiber laser was coupled into the signal port of a (6+1) fiber combiner to test the core loss of the CLS and no loss was found at the output of the CLS. Only a few micrometer of the fiber cladding surface has a mechanical process without any damage on the core, therefore the light confined in the core has no loss when propagating along the fiber. The insert loss only depends on the splicing loss which is lower than 0.1 dB. Therefore, no residual pump and signal light propagating in the inner cladding can be guaranteed by such two cascades homemade CLSs. Fig. 9(b) gives the data of the residual pump power output from the CLS when the maximum pump power 209.4 W is input.

4 Conclusions

A bidirectional-pumped Yb-doped all-fiber laser oscillator with two cascades homemade CLSs was constructed and the laser performances, such as S-P curve, beam quality and distribution, output spectrum and temporal characteristic, are investigated respectively. By employing bidirectional-pump, signal output power is further scaled to 2 kW with a slope efficiency of 76.6%, and the Raman Stokes light is ~47 dB below the signal power even with a 10-m 20 μm/400 μm delivery DCF. The beam quality M^2 is below 1.2 and no residual pump and cladding light are observed. Remarkable power stability (<±0.14%) is also demonstrated because of more uniform temperature distribution on Yb-doped gain fiber by a special thermal management.

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