Signal amplification in ytterbium-doped double-clad fiber amplifier

Liping Chang (常丽萍), Wei Fan (范 薇), Jialin Chen (陈嘉琳), Li Wang (王 利), An Sun (孙 安), Guoyang Li (李国扬), Bai Chen (陈 柏), and Zunqi Lin (林尊琪)

Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800

A diode-pumped Yb-doped double-clad fiber amplifier (YDDCFA) with the narrow bandwidth continuous wave (CW) and pulse input signal is investigated. The input single-mode (SM) signal bandwidth is 10^{-4} nm from a distributed feedback (DFB) fiber laser. The saturated gain of the CW amplification is 11 dB at the forward pump. And besides CW signals, we also amplify pulses with duration of 150 ns and the 1-Hz repetition. The pulse is amplified to 2 W of peak power, 0.31 μJ of energy, 23 dB of gain and less than 6% of stability at the forward pump power of 1.4 W. For higher power, reflections and backscattering can generate the self pulsation in the amplifier. The results are important for the development of the narrow-band double-clad fiber amplifier.

OCIS codes: 060.2320, 060.2430.

In the recent years, rare-earth-doped double-clad fiber lasers and amplifiers have played an important role in a variety of practical and commercial applications, due to good beam quality, high efficiency, high reliability, and compactness[1]. 34-dBm output power with bandwidth of 45 nm in the ytterbium-Doped fiber amplifier has been presented with the lens coupling system[2]. Although the power obtained by some amplifiers is definitely high, the bandwidth is so wide that the output may include some longitudinal and transverse modes. These high power sources can be used in some fields which appeal to the power, not the bandwidth. And in many areas it is not strict in the power but the mode of the signal, which requires the signal with single longitudinal mode and single transverse mode, for example in the front-end system of the inertial confinement fusion (ICF) laser driver. Meantime the high power confined in the single mode core can lead to regular or irregular self-pulsing operating. Indeed, laser instability has been reported in many rare-earth-doped double-clad fiber lasers[3,4].

In this letter, the narrow-band signal amplification in ytterbium-doped double-clad fiber amplifier (YDDCFA) was demonstrated, and the self-pulsation features of the narrow-band diode-pumped fiber amplifier was discussed.

The typical YDDCFAs couple the input signal into the core of the double-clad fiber through dichroic mirrors. However this configuration has some problems because the signal lightwave can additionally propagate in the multi-mode through the first cladding area[5]. To avoid this problem, a multi-mode power combiner with signal feedback was used in the experiment, the signal coupling coefficient of which is about 86%, and the pump is about 94%. This can overcome the disadvantage of the former coupling mean with dichroic mirrors that has a lower coupling efficiency.

Figure 1 illustrates the amplifier configuration. The combiner allows the precise fusion of input fibers around a central signal feedthrough fiber and a dual clad output fiber providing high coupling efficiency over a wide pump wavelength range. The combiner was spliced to the double-clad fiber with an estimated splice loss of less than 1 dB at point A. ISO1 and ISO2 represent the input and output isolators to suppress the backward reflection. A laser diode adopting the optical flat packaging (OFP) technology, with a bandwidth of 5 nm and a central wavelength of 915 nm, was used as the pump source. The double-clad fiber had a silica inner cladding of 130 μm diameter and a silicone external cladding for an NA 0.46 for the pump. The fiber core had a diameter of 6.5 μm, an NA of 0.12, and a cutoff wavelength of 960$\pm$70 nm. The Yb^{3+} concentration was 1.5%. The Yb-doped double-clad fiber length was 4 m.

We amplify the CW signal from phase-shift distributed feedback (DFB) fiber lasers with the advantage of single mode, narrow bandwidth and high stability. The central wavelength is 1052.9 nm, with the bandwidth of 10^{-4} nm. The launched signal power was large enough to insure that the amplifier is in saturation. Using such larger input powers lower the gain of the amplifier and make it less susceptible to seeding lasing from increased ASE if the amplifier is not isolated sufficiently. The pump laser source packaged with the OFP technology had a 0.5 A threshold and generated 3 W at a maximum current of $I = 4$ A. Its approximately 5-nm-wide spectral emission was centered 915 nm at the maximum current.

Figure 2(a) shows the amplifier output power and gain as a function of the diode current, for an injected seed power of $P_{\rm i} = 15$ mW, with the bandwidth of 10^{-4} nm. Figure 2(b) shows the spectrum of the amplified signal at 1052.9 nm, and the average power was decreased 460 times. The diode current was increased from 1 A. We can see that as the pump diode current increases, the output power and gain of the amplifier firstly increases linearly and then decreased gradually. This is due to the saturation because of the high signal and amplified of spontaneous emission (ASE) power. The maximum output power extracted from the amplifier is about 160 mW, while the saturated gain is 11 dB when the pump power coupled into the inner cladding is 2.3 W,

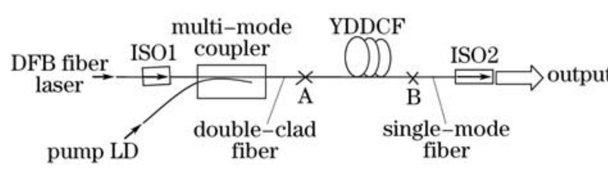

Fig. 1. Configuration of the fiber amplifier.

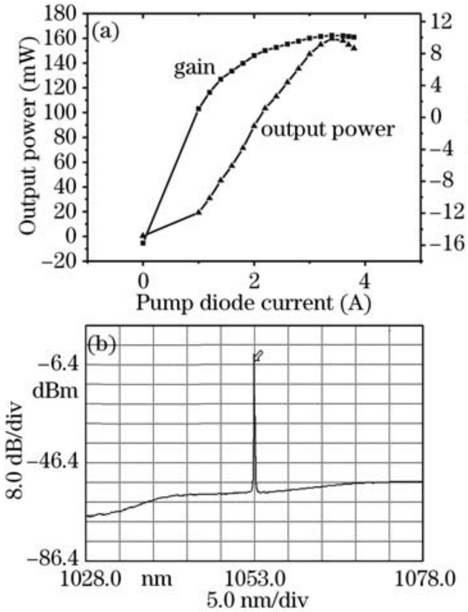

Fig. 2. (a) Output power and gain of the YDDCFA as a function of the pump diode current for a seed power of 15 mW at 1052.9 nm. (b) Spectrum of the amplified signal at 1052.9 nm.

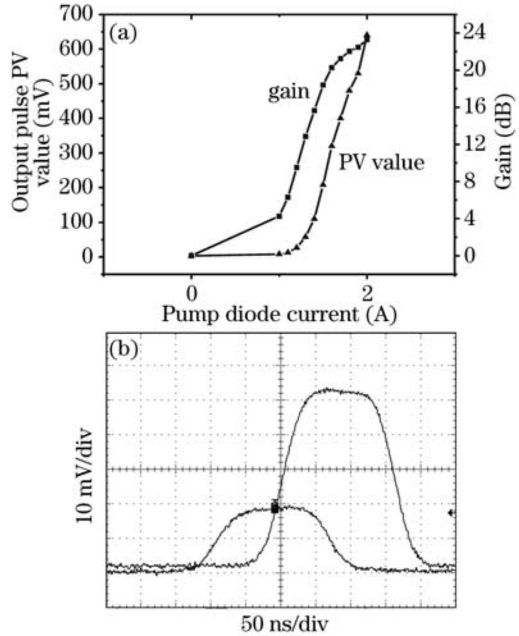

Fig. 3. (a) Output pulse PV value and gain of the amplifier as a function of the pump diode current. (b) Input and output signal pulse shape.

corresponding to the pump diode current of 3.2 A. And we can see that this output signal has high signal-to-noise ratio of 50 dB. It can be predicted that a longer fiber could prove more efficient and this amplifier has a potential to amplify CW signal to significantly higher energy than we obtained. But for the fiber with small core diameter and narrow bandwidth, it will generate a simultaneous problem, for us undesirable, that the longer fiber length will produce the nonlinear optical phenomenon more easily[6], such as the stimulated Brillouin scattering (SBS) or stimulated Raman scattering (SRS), especially for the CW signal.

We next amplified the pulse signal. The CW signal is chopped by an acoustooptic modulator to a pulse duration of 150 ns full-width at half-maximum (FWHM) with a 1-Hz repetition. The repetition rate was low enough to allow for almost complete gain recovery between pulses. Figure 3(a) shows the output pulse peak-valley (PV) value and gain of the amplifier as a function of the diode current with the input pulse duration of 150 ns and the PV value of 3 mV. We firstly amplified the pulse signal to 38 mV through a single-clad fiber amplifier as to saturate the YDDCFA.

Because the ASE the gain was compressed to 23 dB at the forward pump power of 1.4 W, corresponding to the pump diode current of 2 A. And the pulse peak power was approximately 2W, as well as the pulse energy was 0.31 μJ and the high stability of less than 6%, while the pulse shape was not distorted until the signal power is suffice to reach saturation. Figure 3(b) shows the input pulse shape and output pulse decreased 80 times. If we continuously increase the pump diode current, the pulse shape which is distorted seriously can be observed.

This double-clad fiber amplifier has an all-fiber configuration, therefore it has some special advantages, such as higher stability and repeatability than the previous coupled mean with mirrors. And it has less influence from the environment, e.g. vibration, and can be packaged more easily. But the two splicing points have the potential danger to the amplifier. Any splicing point has the light reflection more or less, in despite of the estimated splice loss of both of them less than 1 dB. As the power stored in amplifier becomes higher and higher, the total power reflected by the splicing points is sufficient to generate the pulsation in the amplifier[7].

The output isolator can eliminate back-reflection, but high-performing pig-tailed isolators are not readily available at the power levels and wavelengths of our amplifier, and they are anyhow incompatible with end-pumping of double-clad fibers. So the backscattering and reflection from the splicing points must be paid attention to. Even small amounts reflection power can enhance high pulse energy, which can damage the fiber permanently. There are many reports about the reasons for these mechanisms leading to an irregular self-pulsing instability[8].

Figure 4 shows the oscilloscope traces of output pulse shape as well as the self-pulsation in the amplifier arisen from the back scattering and reflection. The original signal pulse shape is a square wave with the pulse duration of 150 ns. When the pump power launched into the double-clad fiber is increased to about 1.7 W,

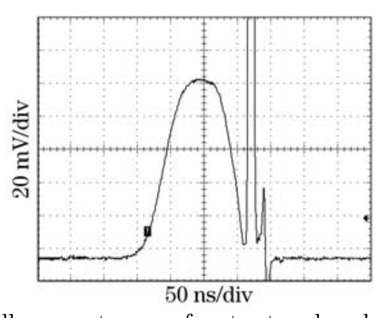

Fig. 4. Oscilloscope traces of output pulse shape and self-pulsation.

corresponding to the pump diode current of 2.4 A. The output pulse shape was distorted terribly, accompanied by a narrower pulse with high peak power. The observed behavior suggested that the self-excitation oscillation occurred in the double-clad amplifier. This behavior also happens in the absence of any input signal. For the launched pump power was higher than some value, the amplifier began to self-Q-switch, producing pulses with high peak power[2]. One approach to avoid the self pulsation is to angle cleave the double-clad fiber end in which case the isolator and the spicing point B are unnecessary, or use the low NA large-mode-area (LMA) fiber, which can reduce the power density in the fiber core but undesirably can guide several higher-order transverse modes[9].

In summary, we have investigated a diode-pumped YD-DCFA for the single-mode CW and pulse input signal with the bandwidth of 10^{-4} nm. The saturated gain of the CW amplification is 11 dB at the forward pump power of 2.3 W with the fiber length of 4m. We also demonstrated amplification of the pulse signal with duration of 150 ns and the 1HZ repetition. The pulse was amplified to 2 W of peak power, 0.31 μJ of energy, 23 dB of gain and less than 7% of stability. Because of the small fiber core and narrow bandwidth, the higher power can produce the self-excitation oscillation arising from the distributed back-scattering, which can limit the gain of the amplifier and sometimes can damage the amplifier permanently. So we should pay more attention to prevent them in the high power amplifiers.

L. Chang's e-mail address is changliping@siom.ac.cn.

References

1. R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, IEEE J. Quantum Electron. **33,** 1049 (1997).
2. J. M. Sousa, J. Nilsson, C. C. Renaud, J. A. Alvarez-Chavez, A. B. Grudinin, and J. D. Minelly, IEEE Photon. Technol. Lett. **11,** 39 (1999).
3. Z. J. Chen, A. B. Grudinin, J. Porta, and J. D. Minelly, Opt. Lett. **23,** 454 (1998).
4. P. Glas, M. Naumann, A. Schirrmacher, L. Däweritz, and R. Hey, Opt. Commun. **161,** 345 (1999).
5. T. Miyazaki, K. Inagaki, Y. Karasawa, and M. Yoshida, J. Lightwave Technol. **16,** 562 (1998).
6. G. P. Agrawal, *Nonlinear Fiber Optics* (3rd edn.) (Academic Press, New York, 2001).
7. S. V. Chernikov, Y. Zhu, J. R. Taylor, and V. P. Gapontsev, Opt. Lett. **22,** 298 (1997).
8. A. Hideur, T. Chartier, C. Özkul, and F. Sanchez, Opt. Commun. **186,** 311 (2000).
9. J. Limpert, A. Liem, H. Zellmer, and A. Tünnermann, Electron. Lett. **39,** 645 (2003).