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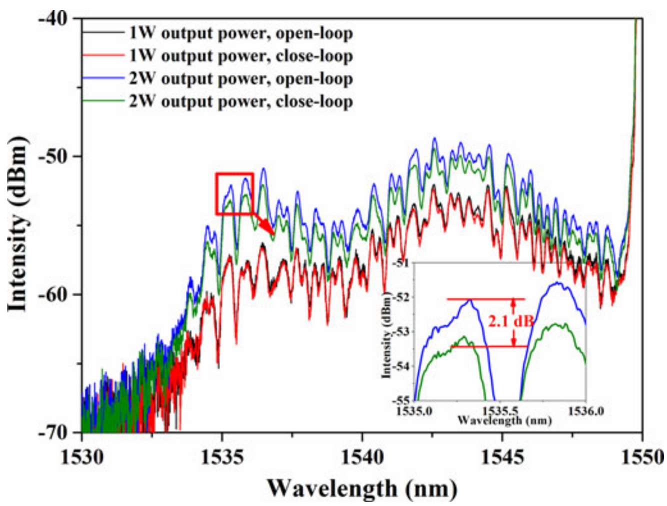

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ASE Suppression in Backward-Pumped Er/Yb Double-Cladding Fiber Amplifier via Cladding Feedback

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Abstract: We demonstrate a backward-pumped 1550 nm narrow-linewidth Erbium-Ytterbium double-cladding fiber amplifier with amplified spontaneous emission (ASE) suppression. Compared with the typical backward-pumped amplifier without feedback, the ASE power can be suppressed by over 2 dB by cladding feedback without other filters. The slope efficiency is 23.2%, which only decreased by 0.4%. The linewidth and relative intensity noise of 4.51 kHz and –92 dBm/Hz are also compared with those of the typical backward-pumped amplifier without feedback.

Index Terms: Amplified spontaneous emission (ASE) suppression, cladding feedback, Erbium-Ytterbium, laser amplifiers, fiber laser.

1. Introduction

Narrow-linewidth lasers around 1.5 μm have been applied in spectroscopy, DWDM communication, and light imaging detection and ranging (LIDAR) because of the “eye-safe” property and low silicon fiber transmission loss [1], [2]. Compared to the well-established methods, e.g., Raman lasers [3] and optical parametric oscillators [4], the Er/Yb-codoped fiber master oscillator power amplifier (MOPA) has minimal mechanical vibrations and optical misalignments and, thus, is being actively explored for the 1.5-μm several kilohertz narrow-linewidth output [5], [6]. Among the pump structures, the backward-pumped amplifier has higher slope efficiency, higher output power than forward-pumping and can suppress the nonlinear effects, especially the stimulated Brillouin scattering (SBS) [7]. However, the backward-pumped amplifier has strong amplified spontaneous emission (ASE) power and obviously limit the output signal to noise ratio (SNR). Moreover, the increasing of ASE will broaden the output linewidth, especially for the single-frequency amplifier [8], [9]. Therefore, the strong ASE power limits the use of backward pumping structure in high power narrow-linewidth amplifier [10], [11].

To suppress the ASE, devices like the narrow-band bulk filter, or the fiber Bragg gating (FBG) must be added, which increases the insertion loss and makes the system much more complicated

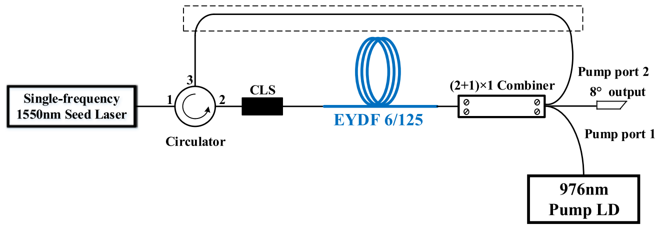

Fig. 1. Experimental setup of the backward-pumped narrow-linewidth EYDF amplifier with cladding feedback. CLS: cladding light stripper. LD: laser diode.

[12], [13]. On the other hand, core feedback of backward ASE can suppress the ASE conveniently without any filters. Nilsson *et al.* re-injected the backward ASE into the core of single-mode active fiber of EDFA. The short-wavelength gain, whose wavelength is shorter than the signal, was suppressed but the long-wavelength gain improved by 4 dB [14]. Jin *et al.* demonstrated a gain-clamped dual-stage L-band EDFA by using backward ASE [15]. By using the secondary pumping effect from the backward ASE in the core, the short-wavelength (1530–1550 nm) ASE could be effectively suppressed and the long-wavelength ASE gain could be notably increased [16]. Therefore, in 1550-nm amplifier, the core feedback of backward ASE could suppresses the ASE with the wavelength shorter than 1550 nm but enhance the long-wavelength ASE gain that may result in lasing. Therefore, core feedback is not suitable for ASE suppression in the 1550-nm amplification.

In this paper, we demonstrate an all-fiber backward-pumped 1550-nm narrow-linewidth Erbium-Ytterbium double-cladding fiber (EYDF) amplifier with ASE suppression by cladding feedback. The backward ASE is coupled into the cladding of the active fiber through a fiber circulator and the pump port of combiner. Compared with the backward-pumped amplifier without feedback, the ASE of cladding-feedback structure is suppressed by over 2 dB, with the slope efficiency decreased by only 0.4%. The spectra linewidth and the relative intensity noise (RIN) are also measured and compared with typical backward-pumped amplifier.

2. Experimental Setup

The schematic of the backward-pumped narrow-linewidth EYDF amplifier with cladding feedback is shown in Fig. 1(a). A commercial polarized narrow-linewidth single-frequency fiber laser with the center wavelength of 1549.96 nm and the linewidth of 700 Hz is used as the master oscillator (seed). The port 1 of the circulator connects to the output port of seed laser, and the port 2 connects to cladding light striper (CLS) and the active fiber sequentially. The circulator bandwidth is 1550 $\pm$ 20 nm. The active fiber used in the experiment is a piece of 5-m-long Erbium-Ytterbium double-cladding fiber (Nufern, SM-EYDF-6/125-HE) with the core and cladding diameters of 6 and 125 μm. The cladding absorption of this active fiber is measured to be 1.8 dB/m at 976 nm. The active fiber is backward cladding pumped by a wavelength-stabilized 976-nm laser diode (LD) through a (2 + 1) $\times$ 1 pump combiner. The pump port 1 of the combiner is spliced to the output fiber of the LD, with the coupling efficiency measured to be 87%. The pump port 2 with the 93% measured coupling efficiency is spliced to the port 3 of the circulator to complete the feedback loop of ASE. Together with the use of CLS, the backward ASE can be directed back to the cladding of amplifier and stripped out. The measured insertion loss of the circulator and the CLS are 0.4 and 0.3 dB, respectively. The end of the signal port at the pump side of the combiner is angle-cleaved at 8° for output coupling. In the next part of the paper, the amplifier with and without cladding ASE feedback are mentioned as “close-loop” and “open-loop,” respectively.

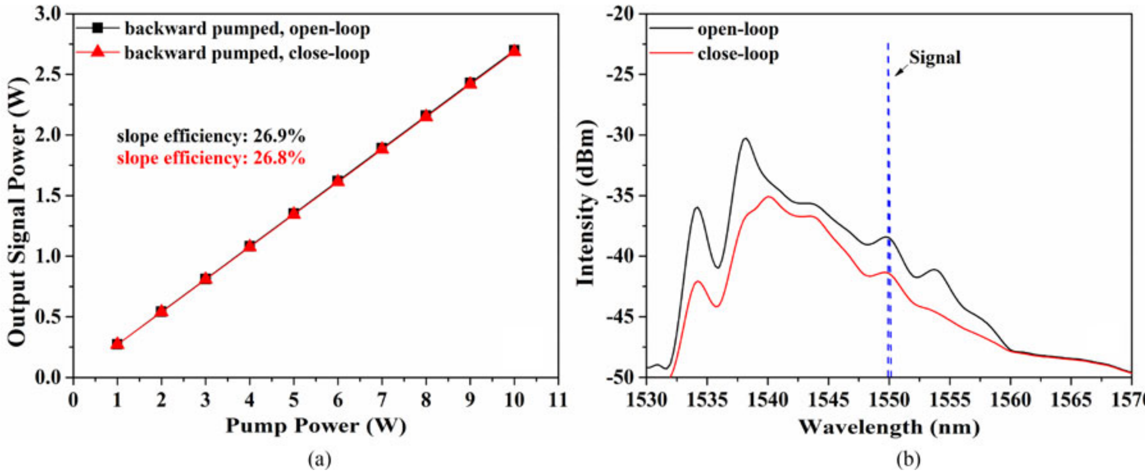

Fig. 2. (a) Performance of the simulate output signal power of open-loop and close-loop. (b) Simulated spectra of open-loop and close-loop.

3. Experimental Results and Discussion

3.1. Numerical Analysis of Cladding Feedback Amplifier

First, we numerical investigated the ASE and power scaling of the amplifier with different structures. The simulation is established by utilizing the steady-state rate equations and power propagation equations [17], [18]. Those equations and the all used parameter values are referred to in [18]. To describe the evolution of cladding feedback ASE power, (1), shown below, is added to the equation groups:

$$\pm\frac{dP_f^{\pm}(z,\lambda)}{dz} = \left\{\Gamma_p[N_2\sigma_{21}(\lambda) - N_1\sigma_{12}(\lambda)] - \alpha(\lambda)\right\} P_f^{\pm}(z,\lambda) + P_0(\lambda)\Gamma_p N_2\sigma_{21}(\lambda) m_s \Delta\lambda. \quad (1)$$

For simplicity, we assume that the Er/Yb doping density is uniform and confined to the core. The $P_f^{\pm}(z,\lambda)$ is the feedback power. The symbol "$\pm$" represents the light transmitted in the forward $(+)$ and backward $(-)$ directions. Notably, the feedback power in cladding (see (1)) has the same power propagation equation and parameters with the signal power in the core expect the overlap factor. The overlap factor of cladding feedback power is Γ_p, which is the same to that of pump power. The core overlap factors Γ_s and the cladding overlap factors Γ_p expressions are derived in [18]. According to the expressions, the calculated Γ_s value is 0.84. The calculated Γ_p value is 0.002.

In this paper, we solved the equations numerically with finite difference method which is reported by Han in 2014 [19]. The signal power is assumed to 10 mW at $z = 0$ point of the active fiber. The $z = 0$ point is the seed signal input end and the $z = L$ is the output end. Considering the backward pump structure, the boundary condition of pump power is $P_p^+(z=0) = 0$ and $P_p^-(z=L) = p_p$. p_p is assumed pump power. Because the backward Er-ASE is fed back to the active fiber and counter-propagates with signal, the P_f condition is $P_f^+(z=0,\lambda) = 0$ and $P_f^-(z=L,\lambda) = P_{ErASE}^-(z=0,\lambda)$. $P_{ErASE}^-(z=0,\lambda)$ is the backward ASE power at the $z = 0$ point. The power of backward Er-ASE $P_{ErASE}^-(z,\lambda)$ correlates with the seed power $P_S^+(z)$ and cladding feedback signal $P_f^+(z,\lambda)$. To get the solution successfully, the value of $P_{ErASE}^-(z,\lambda)$ should be iterated into the boundary conditions at the end of each iteration until the signal power error meet with the request to precision of 1×10^{-6}. The simulated output signal power with different structures as a function of pump power is plotted in Fig. 2(a). For the backward-pumped 5-m-long 6/125 EYDF with close-loop (see the red triangular curve in Fig. 2(a)), the output signal power of is 2.70 W under 10-W pump power, with the slope efficiency calculated to be of 26.8%. It is lower than the case of open-loop (see the black

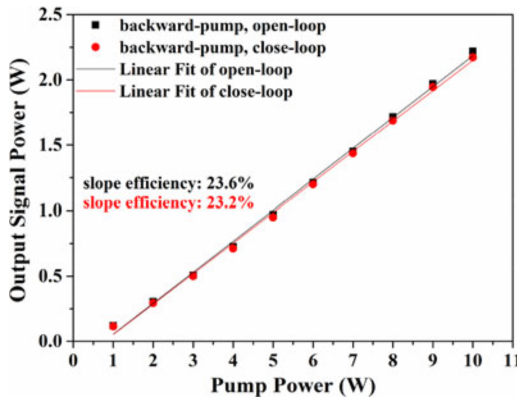

Fig. 3. Output power of backward-pumped amplifiers with and without feedback versus pump power.

square curve in Fig. 2(a)) by only 0.1%. The reason of close-loop having lower efficiency is that the upper-laser-level population is decreased by the feedback of backward ASE. The stimulated ASE spectra without signal of open-loop and close-loop are plotted in Fig. 2(b). The close-loop has less ASE power than open-loop. The maximum ASE suppression is 6.7 dB at 1538 nm. Moreover, the ASE suppression is observed obviously at the short-wavelength, which is shorter than the 1550-nm signal. At the longer-wavelength, i.e., longer than 1550 nm, ASE suppression also can be seen from 1550 to 1560 nm with a weak intensity and the maximum suppression is 3.5 dB at 1554 nm. At the wavelength longer than 1560 nm, there is no ASE suppression. According to this simulated results, the backward pump with cladding feedback can suppress the ASE successfully without significant decrease of slope efficiency. Although the overlap factor of feedback signal P_f is smaller than that of signal in the core, the feedback ASE still could play a role as broadband seed laser counter-propagating in the cladding and can be amplified when it propagates through the doped core. After that, most of amplified cladding backward ASE is stripped out by the CLS at the end of active fiber. The population inversion corresponds to the backward ASE wavelengths is consumed, so that the forward propagating ASE is suppressed. Because the backward ASE fed back in cladding has an overlap factor smaller than that of the core signal and is stripped out by CLS after amplification, it would provide little gain for long-wavelength ASE. Therefore, the cladding feedback can avoid increasing of the long-wavelength ASE.

3.2 Experimental Results of Cladding Feedback Amplifier

The power performance of the amplifier with different feedback-structure is investigated with the seed power of 10 mW. Fig. 3 shows the output power of backward-pumped amplifiers with and without feedback as functions of launched pump power. For the typical backward-pumped amplifier without the cladding feedback (open-loop), the slope efficiency is 23.6%. The maximum output power of open-loop is 2.22-W under 10-W pump power. Then we splice the pump port 2 of combiner and the port 3 of circulator to investigate the performance of cladding feedback. The backward ASE transmits from the 6/125 fiber of circulator to the 105/125 fiber of combiner. Although the core diameter of these fibers are different, the splice loss is very low because the 105/125 fiber has larger numerical aperture (NA $=$ 0.22) than that of 6/125 fiber (NA $=$ 0.18). The backward-pumped amplifier with the cladding feedback (close-loop) launches 2.17-W output power with 10-W pump power. The corresponding slope efficiency is 23.2%. Compared with the open-loop, the slope efficiency of close-loop only decrease by 0.4%, 0.3% more than the simulated result. We infer this difference between the experimental and simulated results is attributed to the decrease of forward ASE power. The measured output power contains the 1550-nm signal power and forward ASE power. We do not have measured the separated signal power and forward ASE power. At the same

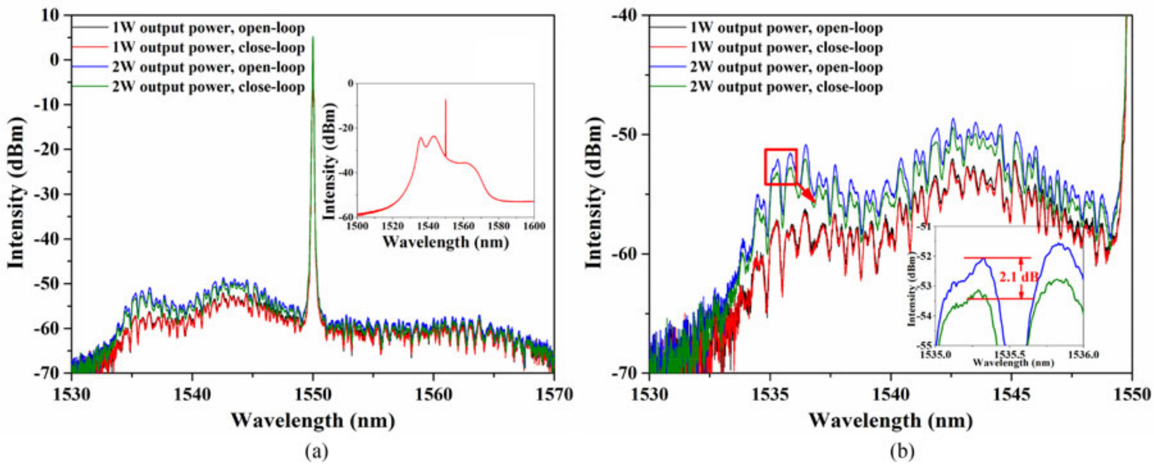

Fig. 4. (a) Output spectra of open-loop and close-loop. (Inset) Spectra of backward ASE. (b) Zoomed spectra from 1530 to 1550 nm. (Inset) Spectra around 1535.4 nm.

time, the simulation does not consider the coupling efficiency of combiner pump port and the splice loss between the circulator and combiner. These losses influence the power of feedback ASE and lead to the deviation. However, according to the output spectra (see Fig. 4) in following, we infer that the suppression of forward ASE by cladding feedback leads to the decrease of measured output power and slope efficiency.

Fig. 4 is the spectra of open-loop and close-loop with 1-W and 2-W output power recorded by an optical spectra analyzer (YOKOGAWA, AQ6375). The spectra of backward ASE is recorded and shown in inset of Fig. 4(a). As shown in the Fig. 4(a), the close-loop structure can suppress the short-wavelength (1530–1550 nm) ASE, which is mainly from 1535 nm to 1545 nm shorter than the signal. The peak wavelength of ASE suppression is corresponded to the peak of backward ASE, which is shown in inset of Fig. 4(a). The reason of short-wavelength ASE obvious suppression is that the backward ASE has enough intensity at short-wavelength to influence the upper-laser-level population. This also can be used to explain why the spectra of 1-W output with and without feedback have the same intensity. With output power increasing from 1 to 2 W, the efficient ASE feedback is built up in the active fiber of close-loop and suppresses ASE power by over 2 dB. The zoomed output spectra from 1530 to 1550 nm is shown in Fig. 4(b). The maximum suppression of forward ASE is 2.1 dB at 1535.4 nm, which is shown in inset of Fig. 4(b). The long-wavelength ASE is suppressed by only 0.1–0.4 dB. Different from core feedback of ASE [15], the cladding feedback of backward ASE via pump port of combiner can avoid the increment of ASE power at long-wavelength. However, since the circulator used in the experiment can only afford limited power, the performance with output power over 2 W was not investigated. If this cladding feedback amplifier can be optimized by choosing high power and low loss component, the suppression of forward ASE will be enhanced.

To investigate the laser linewidth, a delayed self-heterodyne system is adopted, which contains a 50-km-long delay fiber and a 70-MHz acousto-optic modulator. A fiber-coupled InGaAs biased detector with 1.2 GHz bandwidth (THORLABS, DET01CFC) is used to detect the beat signal through a RF signal analyzer. The recorded line shapes of the open-loop and close-loop at 2-W output power are plotted in Fig. 5(a). The 20-dB linewidth of open-loop and close-loop measured are 92.1 and 89.4 kHz, respectively. The corresponding 3-dB linewidth are 4.65 and 4.51 kHz, respectively. Although the cladding feedback can suppress ASE power by over 2 dB, it can hardly influence the output linewidth. This results may demonstrate that the ASE power dose not obviously affect the output linewidth.

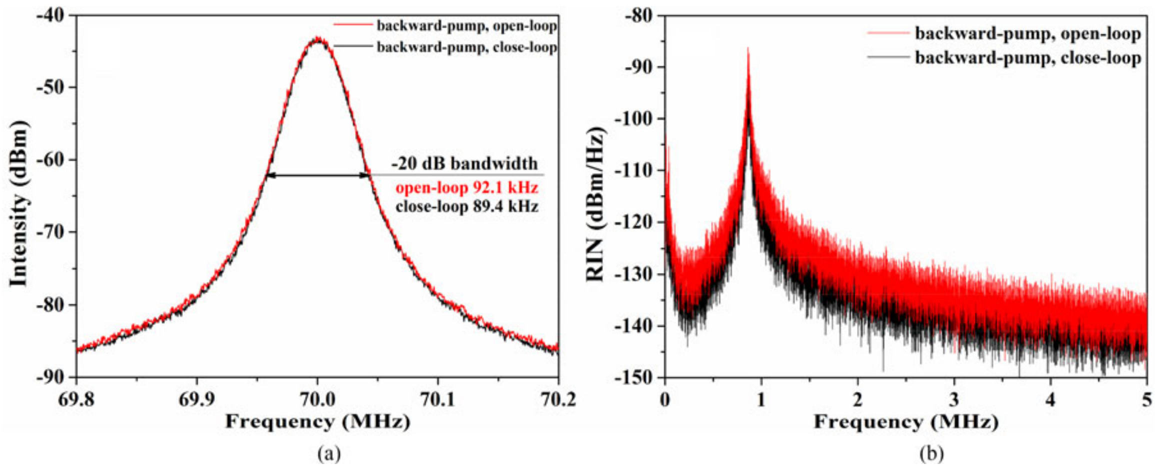

Fig. 5. (a) Lineshapes measured using a delayed self-heterodyne method to the open-loop and close-loop. (b) RIN of amplifiers with 2-W output power.

The relative intensity noise (RIN) of open-loop and close-loop is investigated using the InGaAs detector and RF signal analyzer and shown in Fig. 5(b). When the output power is 2 W, the RIN intensity of close-loop and open-loop is −86 and −92 dBm/Hz, respectively. The cladding feedback can suppress not only ASE power but the RIN intensity as well.

4. Conclusion

We numerically and experimentally investigate an all-fiber backward-pumped 1550-nm narrow-linewidth EYDF amplifier with ASE suppression by cladding feedback. The backward ASE is coupled into the cladding of active fiber via circulator and the pump port of combiner. The results demonstrate this cladding feedback amplifier has over 2-dB ASE suppression with slope efficiency 23.2% due to the short-wavelength ASE reabsorption and amplification. Compared with the backward-pumped amplifier without feedback, the close-loop backward-pumped amplifier has the same linewidth broadening but lower RIN intensity.

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