Analysis of pump-wavelength drift induced stability problems of cladding-pumped EYDFAs

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The impact of pump-wavelength drift on the output power of high power cladding-pumped Er/Yb co-doped fiber amplifiers (EYDFAs) is investigated numerically. The results show that by co-seeding a high power EYDFA with an appropriate auxiliary signal in the 1.0 μm band can not only effectively suppress the spurious lasing and dramatically improve the available output power, but also efficaciously reduce the output power fluctuation induced by the pump-wavelength drift. This technique is helpful to scale the power and improve the power stability of high power EYDFAs, especially for those being pumped around 975 nm.

1. Introduction

High power and stable fiber laser sources in the 1.5 μm band are of great interest for both military and civilian applications such as range finding, free-space communications and particularly light detection and ranging (LIDAR) systems, thanks to its "eye-safe" nature. However, the power-scaling and stabilization of fiber sources in this band have been pursued for many years and not yet been solved very well. The output power still much lower than laser sources in the 1.0 μm band [1]. The difficulty mainly originates from the Yb-ASE in the Er/Yb co-doped fibers (EYDFs) commonly used in the power amplifier stage of a master-oscillator power-amplifier (MOPA) system in this band, which has been proved to be the main factor that limits the power level from EYDFs currently [2-4]. Due to the indirect pumping nature, as the pump rate is getting larger than the energy transfer rate from Yb^{3+} to Er^{3+}, an increasing amount of Yb^{3+} inversion is build up (a.k.a. "bottle-necking" effect), which leads to strong Yb-ASE and degradation of the pump conversion efficiency (PCE). This in turn leads to low threshold of spurious lasing and even detrimental self-pulsing effect harmful to the stability of the laser sources [5]. Besides, the output power stability of high power Er/Yb co-doped fiber amplifiers (EYDFAs) also originates from the thermal drift of the wavelength of the pump sources, especially when the 975 nm laser diodes (LDs) are used. Due to the higher absorption coefficient and lower quantum defect, a 975 nm pump LD is generally preferable than a 915 nm one. However, because the absorption bandwidth of Yb^{3+} at 975 nm is quite narrow, either expensive thermal stabilization measures or very sensitive external wavelength-locking mechanisms have to be employed making 975 nm LDs less attractive as pump sources for high power EYDFAs [6].

Several techniques have been proposed to solve these problems. In Ref. [7], several specially designed fiber Bragg gratings have been used to filter out the Yb-ASE between 1060 and 1080 nm. This approach is effective but complicated and expensive. In Ref. [8], Er/Yb co-doped photonic bandgap fibers which have only week guidance in the Yb emission band are used. However, the results show that the slop efficiency of the amplifier is very low and not suitable for high power amplification. Recently, V. Kuhn and co-workers have demonstrated that by co-seeding an EYDFA with an auxiliary signal at 1064 nm can effectively suppress the Yb-band spurious lasing and self-pulsing effects. Thus the permissible pump power can be increased and the available output power can be improved [5]. But a disturbing high power 1064 nm signal will co-outputted with the useful signal in the 1.5 μm band. Special considerations must be taken to set them apart. Under the support of this experimental work, our theoretical results are finally accepted for publication [9]. In Ref. [9], we show that if the wavelength of the Yb signal is selected properly it can serve as a very good auxiliary pump, amplified and well confined in the core of the fiber, for the 1.5 μm band signal. Thus the power conversion efficiency (PCE) of the EYDFA can be dramatically improved, in the meanwhile as the Yb-ASE and the spurious lasing being suppressed. And by optimization of the active fiber length, the amplified Yb-signal can be well reabsorbed. Following this, a systematic experimental work has been performed to verify the results. A very well agreement between the experimental and theoretical results has been shown [10]. This in turn validates the theoretical mode presented in Ref. [9].

In this letter, Yb signal assisted high power EYDFAs are further characterized numerically. The results show that besides the advantages mentioned above, this technique can also effectively reduce the output power fluctuations caused by the variation of the wavelength of the pump laser diodes. So it is attractive for applications that require high power stability laser sources in the 1.5 μm band.

2. Simulation results and discussion

To study the effect of the variation of the pump wavelength on the output power, several high power EYDFAs are numerically analyzed. The structure of the simulated EYDFA is shown in Fig. 1. A signal at 1550 nm and an optional assisted signal at 1043 nm are first multiplexed by a wavelength division multiplexer (WDM). The power of the two signals is 1 W and 100 mW, respectively. The combined signal is send into the amplifier through the signal port of a pump bundle. A total pump power of 300 W is assumed in the simulations. The active fiber is a double-clad EYDF with a hexagonal inner cladding. The core diameter is 30 μm. The cladding face-face diameter is 350 μm. The numerical aperture of the core is 0.174. The Yb^{3+} and Er^{3+} concentration in the core of the EYDF are 3.526×10^{26} ion/m^3 and 2.450×10^{26} ion/m^3, respectively. The life-time of the Er^{3+} levels $^4I_{13/2}$ and $^4I_{11/2}$ and the Yb^{3+} level $^2F_{5/2}$ are 10 ms, 1 ns, and 1.5 ms, respectively. The Yb and Er cross-sections are shown in Fig. 2. The absorption cross-sections are experimentally measured and the corresponding emission cross-sections are calculated according to the McCumber theory [11]. In all the simulations, fiber lengths of EYDFAs have been optimized at a pump power of 300 W. The optimized fiber lengths (L_{opt}) are determined by a recursive procedure with $\Delta L = 0.1$ m until $\Delta P_{s,out} / \Delta L < 1$ W/m (for cost effectiveness) is satisfied, where $P_{s,out}$ is the output power of the amplified signal and L is the fiber length. The wavelength of the Yb-band signal is determined by numerical optimization. The results show that for the EYDFAs mentioned above the optimized wavelength is ~1043 nm.
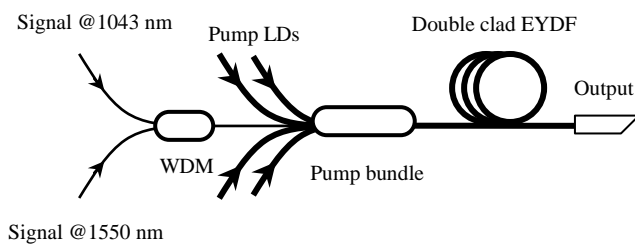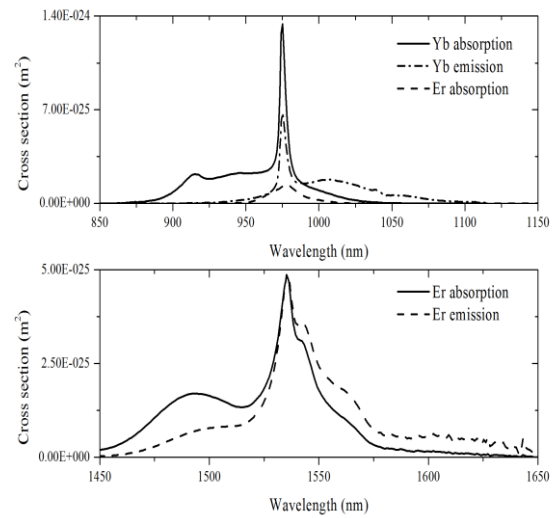

Fig. 2. Absorption and emission cross sections of the active fiber.

The two commonly used pump wavelengths for an EYDFA are 975 nm and 915 nm. Fig. 3 compares the output power variation of EYDFAs assisted and unassisted by the Yb-signal, as the pump wavelength changing ±5 nm relative to 975 nm and 915 nm, respectively. The pump power is 300 W. The optimized fiber lengths for the unassisted EYDFAs are 5 m and 9.8 m when pumped at 975 nm and 915 nm, respectively. While for the assisted EYDFAs, the optimized fiber lengths are increased to 16.7 m and are the same for both pump wavelengths. From the figure we can see that for the unassisted EYDFA, the output power change induced by the pump wavelength variation is much larger for EYDFAs pumped at 975 nm than those pumped at 915 nm. The maximum relative power changes are 26.7% and 3% for the 975 nm and 915 nm pumped EYDFAs, respectively, as the pump wavelength changing ±5 nm. So for applications where the output stability is important, the 915 nm pump is generally preferable. The figure also shows that the output power of EYDFAs pumped around 915 nm is higher than those pumped around 975 nm. This is mainly because the absorption coefficient around 915 nm is much lower than that around 975 nm. Its power is absorbed in a more distributable manner and the "bottle-necking" effect is lower.

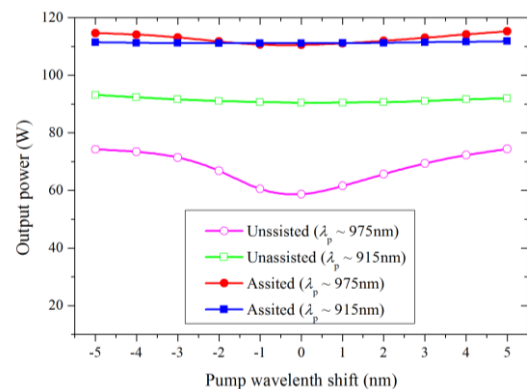*Fig. 1. Schematic of the Yb signal assisted EYDFA.*

Fig. 3. Comparison of output power variation of assisted and unassisted EYDFAs vs. pump wavelength shift.

From Fig. 3, it can be seen that when assisted with a 100 mW signal at 1043 nm, the output power of EYDFAs pumped in both pump band are notably improved. The relative power change with the variation of the pump wavelength is also reduced. For the ~975 nm pumped EYDFAs, the maximum relative power change is lower than 4% when the pump wavelength changes ±5 nm. And for the ~915 nm pumped ones, the maximum relative power change is below 0.6%. These results show that by co-seeding a high power EYDFA with a proper Yb signal not only dramatically increases the output power, but also effectively improves the output stability. In practice, the thermal drift of the pump wavelength is typically in the range of ±1 nm. From Fig. 3, the corresponding relative power variation is below 0.5% and 0.1% for a 975 nm and 915 nm pump, respectively. Moreover, because the optimized fiber length and assisted signal are all the same, for the Yb-signal-assisted EYDFA the output power is almost the same when pumped at 975nm or 915 nm. However, this conclusion is only valid at the designed pump power, the pump power at which the active fiber length is optimized. Fig. 4 shows the output power as a function of the pump power of the Yb-signal assisted EYDFAs pumped at 975 nm, 975±1 nm, and 915 nm, respectively. The inset shows the region around the pump power of 300 W. From the figure we can see that the maximum power difference is only about 0.6 W at 300W, corresponding to a relative power variation of 0.54%. As the pump power deviates from the designed power, the power difference between the 915 nm pumped EYDFA and the 975 nm pumped one is relatively larger. However, for the EYDFAs pumped around 975 nm, the output power is always almost the same with the change of the pump power. Because the quantum defect is smaller, for Yb-assisted EYDFAs a pump wavelength around the 975 nm would be more preferable.
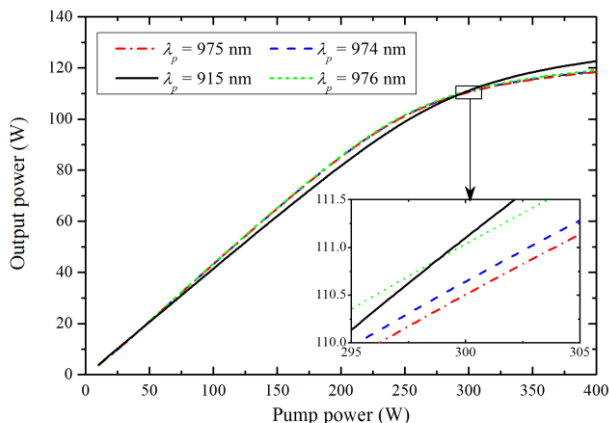
3. Conclusions

In this paper, pump wavelength induced output stability of high power cladding pumped EYDFAs have been numerically investigated. The results show that for conventional EYDFAs, the output power variation caused by the pump wavelength drift is much larger when pumped at ~975 nm than pumped at ~915 nm. By co-seeding a high power EYDFA with an appropriate auxiliary signal in the 1.0 μm band can not only effectively suppress the spurious lasing, but also notably improve the available output power, and efficaciously reduce the output power fluctuation induced by the pump-wavelength drift. This technique is attractive to improving the power and stability of EYDFAs, especially for those pumped at ~975 nm.

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Fig. 4. Output power vs. pump power of Yb-assisted EYDFAs pumped at different wavelengths.

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