A Comprehensive Experimental Investigation on Power Consumption of Multi-mode Pumped Super L-band EDFAs

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Abstract *This work tries to find out whether there is benefit to use multi-mode pumping in super L-band EDFAs in terms of the power consumption. Experiments are designed to eliminate the impact of the EDF's host glass as well as to consider different operation conditions.*

Introduction

The *super L-band* erbium doped fiber amplifier (EDFA) provides 50% more gain bandwidth than that of the conventional *L-band* EDFA, covering a wavelength range of 1575 ~ 1527 nm (6 THz). It will be the building block of the future *super C/L band* solutions for optical telecom links [1].

The erbium doped fiber (EDF) used in this type of amplifier is based on the phosphor-silicate glass (P-Si). In P-Si, the Er^{3+} ions show weaker excited state absorption (ESA) and smaller gain ripple, compared to the Er^{3+} ions in the alumino-silicate glass (Al-Si) which is the material host of conventional EDFs. As a result, P-Si EDFs can provide much higher gain at >1620 nm region. The P-Si glass favours the energy transfer between the Yb^{3+} and Er^{3+} ions. If co-doping Er^{3+} and Yb^{3+} ions in P-Si, Yb^{3+} ions can be pumped by multi-mode (MM) laser and then transfer the energy to Er^{3+} ions for signal amplification. Since the MM pump diode is much cheaper than the single-mode (SM) pump diode, using Er^{3+}/Yb^{3+} co-doped fiber (EYDF) has the potential to significantly lower the fabrication cost of the *super L-band* EDFA. Before moving forward to replace the SM pump by the MM pump, the amplifier performances using MM pumping still needs to be evaluated, among which the power consumption is of the most importance.

Numerical simulations [2] have been done to analyse the pump power consumption of P-Si EYDF using MM pumping, but a comparison to the SM pumping is missing and they are not for the *super L-band*. Our previous work [3] experimentally compares two P-Si EDFs, one doped with Er^{3+} ions only and the other co-doped Er^{3+} and Yb^{3+} ions. They have shown similar gain properties and their ultimate electrical power consumptions are comparable. The result is encouraging but there still remain two concerns. Firstly, since the comparison is between two different fibers, it doesn't exclude the impact of the glass matrix, to which the EDF's gain properties and the power consumptions are very sensitive [4]. Secondly, the comparison is done under a fixed fiber length, therefore, it didn't cover a wide range of amplifier's operation conditions. After all, no definite conclusion can be drawn yet regarding the benefit of using MM pumping in terms of the power consumption.

In this paper, investigations are done on the same EYDF for *super L-band* amplification so that the glass host for SM (1480 nm) and MM (915 nm) pumping keeps identical. In order to cover various operation conditions, three parameters are swept in the experiment: the input signal power, the gain tilt and the length of the EYDF. A sophisticated power consumption comparison is done and we conclude that the MM pumping is more power efficient in most cases.

Experiments

The experimental setup is shown in Fig. 1(a). The

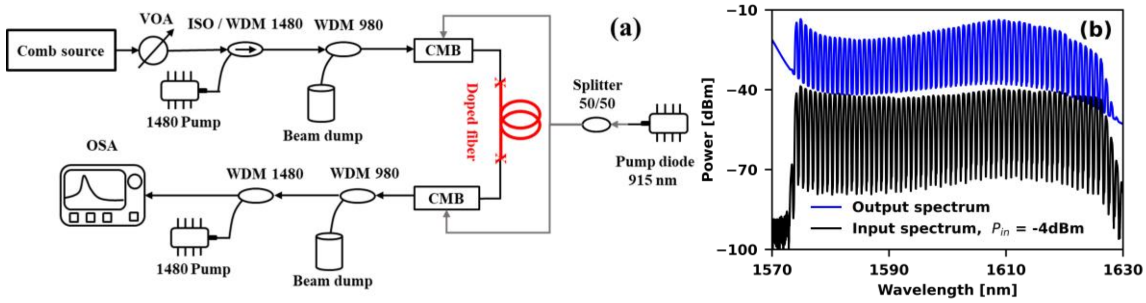

Fig. 1: (a) Experimental setup; (b) typical input and output signal spectra. WDM: wavelength-division multiplexer, VOA: variable optical attenuator; CMB: signal/MM-pump combiner.

signal source is a filtered amplified spontaneous emission (ASE) light covering the *super L-band*. Its total power is tuned (in step of 2 dB) from -4 to 14 dBm, by a variable optical attenuator (VOA). The fiber under test is a double-clad P-Si EYDF from Université Laval, Canada [3]. Pairs of SM WDMs and signal/MM-pump combiners (CMBs) are connected in a cascade way so as to allow both SM (1480 nm) and MM (915 nm) pumping in the same setup. 980/L-band WDMs are inserted in the setup to filter out the 1 µm ASE light generated by the Yb^{3+} ions. Fig. 1(b) show the typical spectra of input (-4 dBm power, 4 dB gain ripple) and output signals. The input/output signal powers and the pump powers are calibrated to the two ends of the EYDF so that the impact of the passive devices is removed.

The workflow of the experiment is as the following. Firstly, we set the pump to be 1480 nm SM, fix the fiber length and pick an input signal power from the range of -4 ~ 14 dBm. Then, we tune the SM pump power to reach a set of minimum target gains within the region of 6~15 dB, each corresponds to a different gain tilt. Therefore, for each input signal power and for each fiber length, we obtain several gain curves with different gain tilts. In addition, we guarantee that one of these gain curves corresponds to the minimum gain ripple which is defined as: $(G_{\max}-G_{\min})/G_{\min}$. After that, the pump is shifted to 915 nm MM. Its power is thereafter adjusted to obtain gain curves whose minimum gain levels match those obtained by 1480 nm SM pumping. Finally, the experiment is repeated for fiber lengths of 55, 50, 45, 40, 35, 30, 25 and 20 m. Only for 50 and 55 m fibers, the gain curve corresponding to the minimum gain ripple can not be reached due to the maximum available pump power.

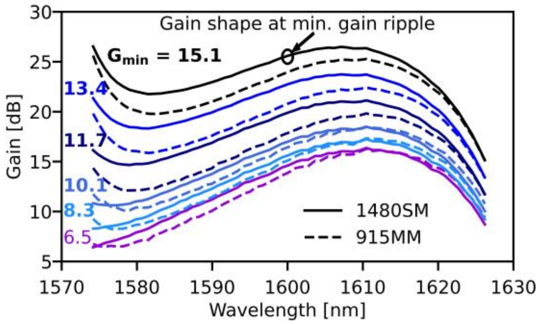

Fig. 2 : Gains of 45 m EYDF under input power of -4 dBm.

Results and Discussion

Fig. 2 shows the gains curves collected using 45 m EYDF with input signal power of -4 dBm. The solid/dashed lines are obtained by SM and MM pumping respectively. The black solid curve represents the gain obtained by SM pumping, with minimum gain ripple of ~ 75% and with a minimum gain of 15.1 dB. The black dashed curve is the gain obtained by MM pumping and its minimum gain is adjusted to be the same as that of the SM pumping gain (15.1 dB). It is evident that the gain curves obtained using SM and MM pumping are significantly different, although they are generated by the same piece of EYDF and the host glass matrix are exactly the same. We believe that this is the site depending pumping phenomenon [5]. The spectroscopic property of an Er^{3+} ion is strongly dependent on its location in the core, *i.e.* the ambient glass matrix. The SM pump light is guided in the core. It interacts more with the Er^{3+} ions in the center of the core. In contrast, the MM pump light propagates in the cladding with uniformly distributed power intensity. It interacts evenly with the Er^{3+} ions across the core. For SM and MM pumping, the distributions of the inverted Er^{3+} ions that contribute to the optical gain are different, leading to a distortion in the gain profile. An interesting observation is that the minimum gain ripple of MM pumping (~ 69%) is better than that of SM pumping (~75%), indicating that Er^{3+} ions in some locations of the core seem to have better spectroscopic properties than in the other locations. This means that there is still room for further engineering the glass matrix and improving the EYDF's performance.

Table 1: E/O efficiencies of cutting-edge pump diodes.

Pump diode	EO Efficiency	Ref.
980 SM	18.2%	[6]
1480 SM	7.9%	[7]
915 MM	46%	[8]

We calculate the MM-SM power consumption ratios in four ways: 1) optical power ratio between 915 MM and 1480 SM; 2) optical power ratio between 915 MM and equiv. 980 SM (1480 SM power ×1480÷980); 3) electrical power ratio between 915 MM and 1480 SM; 4) electrical power ratio between 915 MM and equiv. 980 SM. The electrical power consumptions are calculated using the E/O efficiencies of the state-of-the-art commercial pump diodes listed in Table 1 [6–8]. The way to estimate the equiv. 980 SM optical power is in fact a conservative one because 1480 SM pumping usually leads to a more uniform Er^{3+} inversion distribution along the fiber and thus has higher quantum pump conversion efficiency than the 980 SM pumping.

Firstly, we compare the power consumption ratios under the condition that the gain curves are all with the minimum gain ripple. In a real amplifier product, the internal fiber gain profile is usually set in this way so that the depth of the gain flattening filter can be the shallowest. Fig. 3 illustrates the results for different fiber lengths and input signal powers. The optical power ratio can be as low as ~ 2.56 (915 MM to 1480 SM) and ~ 1.69 (915 MM to equiv. 980 SM) and the electrical power ratio can be as low as ~ 0.43 (915 MM to 1480 SM) and ~ 0.66 (915 MM to equiv. 980 SM). Almost for all the input signal powers, the electrical power consumption of using MM pumping is lower than those using SM pumping. Note that we have plotted the data after filtering out those having error ≥ 0.3 dB of the minimum gain, therefore a few points are missing for some fiber lengths.

Secondly, we select the gain curves that use the minimum SM/MM pump power to achieve a set of nominal minimum gains (6, 8, 10 and 12 dB, within a window of ±0.2 dB). For example, for a certain target minimum gain and for a fixed input power, we pick the two gain curves that consumes the least SM and MM pump powers, no matter what fiber length it is and what gain tilt it is. Then we calculate the ratios. Fig. 5 plots the two exemplary gain curves at 6 dBm input signal power and nominal target gain of 8 dB. It can be seen that the fiber lengths and the gain tilts are different for the SM and MM pumping. Fig. 4 summaries the results. The general trend shows that the power ratio (electrical or optical) tends to decrease with the increase in minimum gain. For this specific *super L-band* EYDF, the MM pumping prefers higher target gain, *i.e.* longer fiber length, to be more power efficient than the SM pumping. After all, as long as the gain is larger than 8 dB, the MM pumping always consumes less electrical power than the SM pumping.

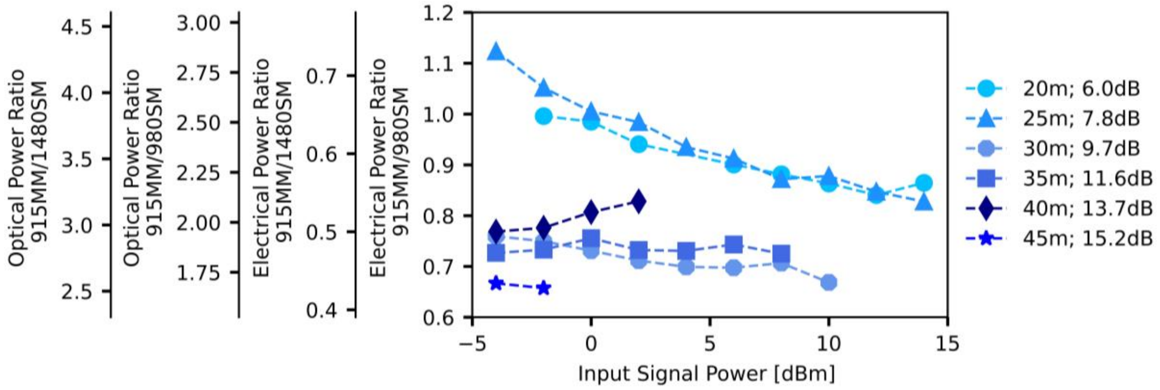

Fig. 3: Electrical and optical power ratios between MM pumping and SM pumping with gain ripple being fixed to their minimum values (75% for SM and 69% for MM).

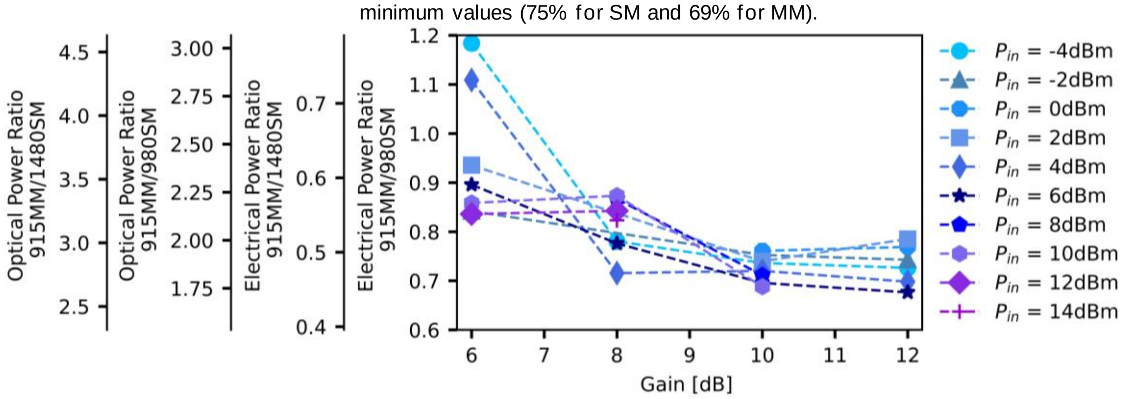

Fig. 4: Electrical and optical power ratios between MM pumping and SM pumping at certain target minimum gain levels and at different input signal powers.

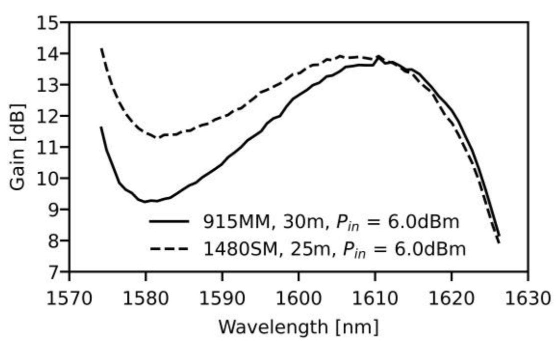

Fig. 5 : Exemplary gain shapes for input signal power of 6 dB and target minimum gain of 8 dB.

Conclusion

We compared the optical and electrical power consumptions using SM and MM pumping within the same *super L-band* P-Si EYDF. Two methods of comparison, one with fixed gain tilt and the other with fixed target minimum gain, have been done. The experimental results prove that, as long as the glass matrices are close enough (for example both the EDF and the EYDF are optimized to have the best glass composition), MM pumped EYDFA can be more power efficient than the SM pumped EDFA. Tens of percentage of electrical power can be saved by using MM pumping in addition to the fabrication cost saving.

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