8W 1952nm Highly Efficient Brillouin-free Single Clad TDFA

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Abstract *We report the performance of a robust and compact two stage single clad TDFA delivering an output power of 8 W at 1952 nm, with slope efficiency of 70 % and input dynamic range > 30 dB.*

Introduction

Accurate simulations of TDFAs[1] are possible through fundamental characterization of the studied fibers used in a simple three level model[2]. In previous publications, we have demonstrated up to 5 W of output signal power out of a two stage single clad (SC) TDFA[3–5]. We have previously demonstrated a slope efficiency of 60 %, which is significantly less than the theoretical maximum of 80 %. In this paper, we investigate the slope efficiency of several SC Thulium-doped fibers (TDF) in a saturated regime. We then demonstrate a two stage SC TDFA that delivers a record of 8 W of stable output power at 1952 nm with a 70 % slope efficiency. We also compare the experimental data with our simulation. Such a high power broadband amplifier has many applications in telecommunications or in LIDAR.

Experimental setup

The two stage SC TDFA topology is shown in Fig. 1. Signal light from a single-frequency ($\Delta\nu$<7 MHz) laser source was coupled into the pre-amplifier. This high gain stage was a length of 4.3 m of iXBlue IXF-TDF-4-125 (4µm) counter

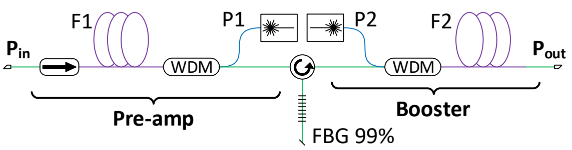

Fig. 1: Two stage TDFA topology.

pumped by P1 at λ_p≈1560 nm. The pre-amplifier was optimized following a study of the performance of single stage amplifiers on active fiber length[3,5]. The inter-stage element was an ASE filter with a bandwidth of 1 nm made from a circulator and a FBG. The second stage was co-pumped with P2, another pump source at λ_p≈1560 nm. Three different fibers F2 were investigated for the second stage: 2 m of OFS TmDF200, 2 m of iXBlue 4µm, and 1.2 m of iXBlue IXF-TDF-5-125 (5µm) respectively. The second stage fiber length was chosen to minimize the onset of stimulated Brillouin scattering (SBS). The SBS threshold of the booster stage was estimated to be 12.5 W[6], far above our output power level for the iXBlue 4µm fiber.

Pre-amplifier performance

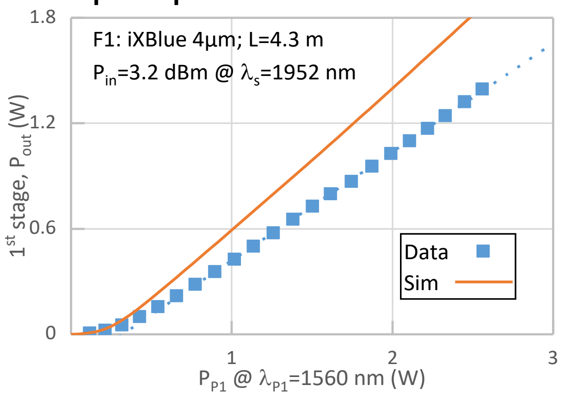

Fig. 2: Pre-amplifier P_{out} vs P_{P1}.

The first stage was designed to be a pre-amplifier focused on high gain and high input power (P_{in}) dynamic range. Fig. 2 shows the output power (P_{out}) versus pump power (P_{P1}). We measured a slope efficiency ($\eta=\Delta P_{out}/\Delta P_p$) of 62 % in a saturated mode, delivering 1.4 W of P_{out} at full P_{P1}.

The output spectrum of the pre-amp is shown in Fig. 3 in a solid line with its simulation in dashed line. We estimated the bandwidth BW at 10 dB width below the ASE peak. The estimated ASE bandwidth of the pre-amplifier was found to be 169 nm.

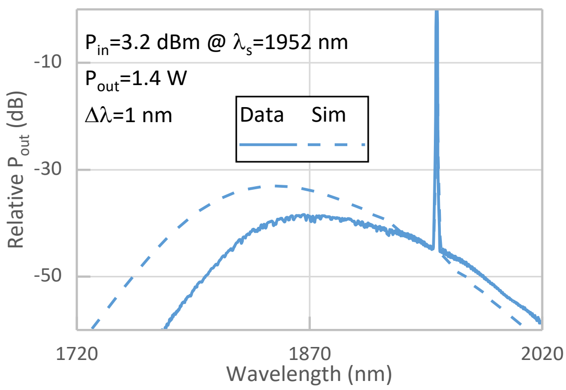

Fig. 3: Output spectrum of the pre-amplifier.

In order to prevent self- lasing and to have a high P_{in} dynamic range, P_{P1} was set to 1 W. The measured and simulated gain (G) and noise figure (NF) versus P_{in} are plotted in Fig. 4. The pre-amplifier produced a small signal gain greater than 35 dB with a NF lower than 7 dB.

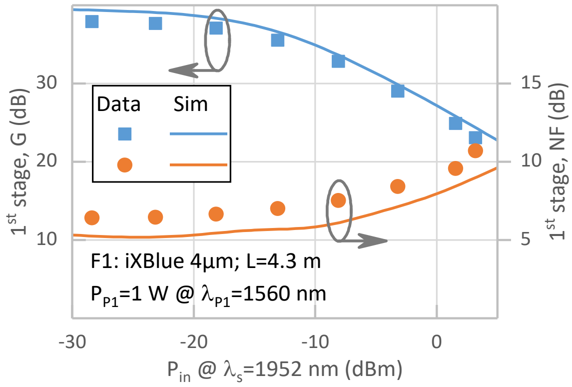

Fig. 4: Pre-amplifier G & NF vs P_{in}.

This pre-amplifier delivered G > 35 dB and NF < 7 dB for P_{in} < -20 dBm with a high dynamic range of 33 dB which is suitable as an input for our booster stage.

Booster stage performance

To have high efficiency in the booster stage, three different SC TDFs were evaluated. We first investigated the slope efficiency versus P_{in}. Fig. 5 shows the measured and simulated η for each fibers versus P_{in}. We note that the experimental slope efficiency is slowly increasing with P_{in} over a 30 dB range: from 60 % to 70 % with the OFS configuration, from 47 % to 60 % with the iXBlue 4µm configuration, and from 36 % to 53 % with the iXBlue 5µm configuration, respectively. For all the configurations, the simulation over-estimated the slope efficiency, and is close to the theoretical maximum λ_p/λ_s=80 %.

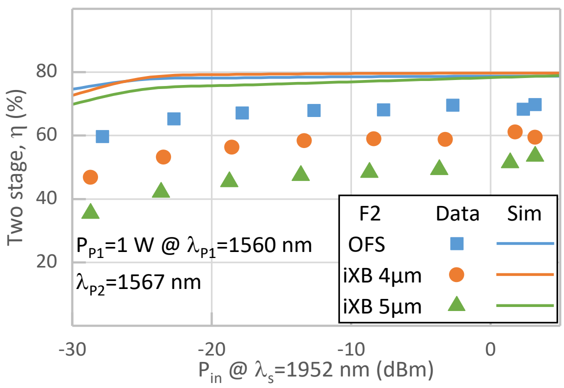

Fig. 5: Two stage η vs P_{in} for 3 different SC TDF.

Next, we then measured the amplifier output for a saturating P_{in}. Fig. 6 shows the measured and simulated P_{out} for the three different fibers. For all three fibers, we were able to reach an output power greater than 5 W. At P_{out} = 5 W, the differences between the experimental and simulated data are 0.5 dB with the OFS configuration, 1.4 dB with the iXBlue 4µm, and 1.6 dB with the iXBlue 5µm, respectively. For the OFS configuration, the pump was increased to its maximum P_{P2} of 11 W and the output power of the two stage amplifier reached a maximum P_{out} of 8 W: no residual pump was observed at the output of the fiber.

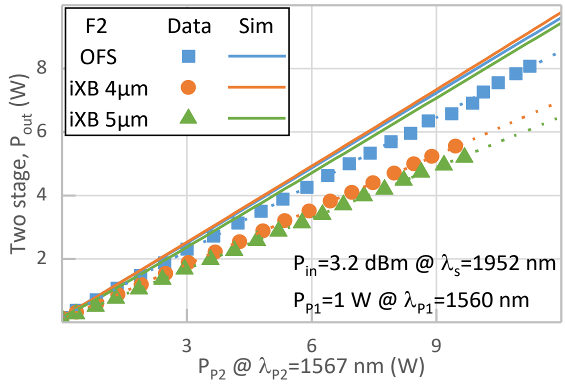

Fig. 6: Two stage P_{out} vs P_p for 3 different SC TDF.

In order to test the stability of our amplifier at a P_{out} of 5 W power over a 6 hour period. The power stability was measured to be better than 2 % peak-to-peak over this period, showing no thermal effect in the amplifier. Also no SBS or other non-linear effects were observed for the single-frequency input signal during this measurement[6].

Next the pump P2 was set to 8 W and we studied the dynamic range of our amplifier for three F2 fibers. Fig. 7 shows the evolution of G versus P_{in} for the three different fiber F2. We observed an input signal dynamic range of 33 dB. For this pump power, only the OFS configuration delivered performance robust enough to have an output power of 5 W over the whole P_{in} dynamic range.

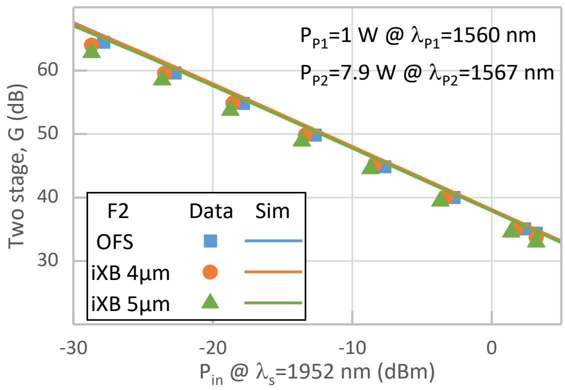

Fig. 7: Two stage G vs P_{in} for 3 different SC TDF.

In order to estimate the bandwidth of the amplifier, the inter-stage filter was replaced with an isolator. As an example, the output spectrum for an output power of 5 W with the iXBlue 4µm configuration is displayed in Fig. 8 with its

simulated curve. The 10 dB ASE BW was estimated to be 128 nm, indicating a broad operation bandwidth.
The noise figure of the amplifier, measured using an inter-stage isolator, was lower than 7 dB for P_{in} of -5 dBm.

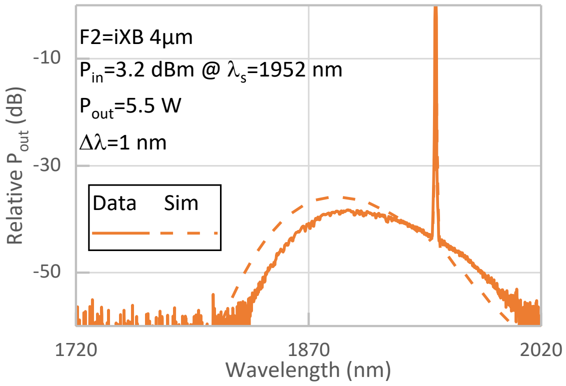

Fig. 8: Output spectrum for one and two stage.

Discussion

For the three commercial TDFs in the booster stage we measured a difference between the simulated and experimental slope efficiencies. In saturated regime, the amplifier exhibited a slope efficiency of 70 % with the OFS configuration, 57 % with the iXBlue 4µm configuration, and 53 % with the iXBlue 5µm configuration, whereas the simulation exhibited a slope efficiency of 80 % for the three configurations. We note that the OFS is the lowest doped fiber and the iXBlue 5µm has the highest doping.
As the fibers were pumped by sources around 1560 nm, we were able to observe blue (probably $^1G_4$ -> $^3H_6$ centered around 460 nm) fluorescence for every fiber. The blue fluorescence was observed to be more prominent with the iXBlue 5µm and less prominent with the OFS fiber. However, we do not know the composition of the different fibers and we cannot draw quantitative conclusions from these observations. The possible answer for this difference in fluorescence might lie in the variation of material composition of the fibers. The difference in slope efficiency between simulation and experiment indicates that some loss mechanism is not taken into account for single clad fibers in-band pumped around 1560 nm.

Conclusions

We have demonstrated a compact and robust two stage single clad amplifier delivering an output power of 8 W at 1952 nm with a 70 % slope efficiency. Input signal dynamic range greater than 30 dB and small signal gain greater than 60 dB were demonstrated. The bandwidth of the amplifier was estimated using the ASE spectrum, yielding a broad bandwidth of 128 nm.
The topology was optimized using a simulation tool, allowing a compact, robust, and efficient design. Through the comparison of the slope efficiency of three different commercial second stage active fibers of our amplifier design we could achieve efficiency greater than 60 % in a saturating regime.
The differences in slope efficiency between the simulation and the experimental data for the three different commercial fibers are under investigation and will be the subject of a later publication.

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