Realization and optimization of a 1 ns pulsewidth multi-stage 250 kW peak power monolithic Yb doped fiber amplifier at 1064 nm

Bertrand Morasse*, Estéban Plourde
CorActive High-Tech, 2700 Jean-Perrin, suite 121, Québec, QC, Canada, G2C 1S9

ABSTRACT

We present a simple way to achieve and optimize hundreds of kW peak power pulsed output using a monolithic amplifier chain based on solid core double cladding fiber tightly packaged. A fiber pigtailed current driven diode is used to produce nanosecond pulses at 1064 nm. We present how to optimize the use of Fabry-Perot versus DFB type diode along with the proper wavelength locking using a fiber Bragg grating. The optimization of the two pre-amplifiers with respect to the pump wavelength and Yb inversions is presented. We explain how to manage ASE using core and cladding pumping and by using single pass and double pass amplifier. ASE rejection within the Yb fiber itself and with the use of bandpass filter is discussed. Maximizing the amplifier conversion efficiency with regards to the fiber parameters, glass matrix and signal wavelength is described in details. We present how to achieve high peak power at the power amplifier stage using large core/cladding diameter ratio highly doped Yb fibers pumped at 975 nm. The effect of pump bleaching on the effective Yb fiber length is analyzed carefully. We demonstrate that counter-pumping brings little advantage in very short length amplifier. Dealing with the self-pulsation limit of stimulated Brillouin scattering is presented with the adjustment of the seed pulsewidth and linewidth. Future prospects for doubling the output peak power are discussed.

Keywords: pulsed fiber amplifier, solid core double cladding fiber, 976 nm pump bleaching, counter-pumping, DFB and Fabry-Perot current driven diode, stimulated Brillouin scattering, ASE rejection, single pass and double pass

1. INTRODUCTION

Yb fiber laser and amplifier are now widely spread due to their high efficiency, low cost and monolithic integration[1]. These active fiber devices are used to generate high power CW laser, but there is also a need for short pulse high peak power signal for applications such as material processing[2]. One of the main advantages of fiber lasers is the long interaction length of the fiber to distribute the thermal load. But this becomes an inconvenient when comes the time to amplify high peak power signal because of the onset of non-linear effects that scale with propagation length[3]. A good beam quality is required in many application such as frequency doubling, thus enlarging the core area of the fiber is not a simple solution: this minimizes non-linear effects but the onset of higher orders modes in the fiber degrades the beam quality. Adding more active dopant in the fiber length to decrease the overall length is limited due to photodarkening[4]. Several solutions were proposed to offer fiber with large mode area, small interaction length and good beam quality such as photonics crystal or air silica holey fibers[5,6]. Nevertheless, those devices are complicate to fabricate, cannot be packaged tightly or easily spliced with other components.

In this paper, we propose a simple way to amplify high peak power pulse using standard double cladding fiber used in a simple and low cost monolithic configuration. A current modulated diode allows the generation of flexible short pulses at low cost that can then be amplified in a multi stage amplifiers using off the shelf components. The high peak power can be achieved by relying on highly doped phosphosilicate Yb fiber that be operated efficiently with very short length when pumped at 975 nm. Those solid core fibers can be spliced easily to other standard silica based components and be packaged tightly with small coiling.

*Bertrand.morasse@coractive.com; phone 1 418 845 2466; www.coractive.com

Bertrand Morasse and Estéban Plourde, "Realization and optimization of a 1 ns pulsewidth multi-stage 250 kW peak power monolithic Yb doped fiber amplifier at 1064 nm," Proc. SPIE, Photonics West, LASE, Fiber Lasers XIV: Technology and Systems, (2017)

DOI abstract link: http://dx.doi.org/10.1117/12.2247826

2. EXPERIMENTAL CONFIGURATION

2.1 Overall setup

The schematic of the overall setup is presented on Figure 1. The seed source consists of a 1064 nm Fabry-Perot or distributed feedback (DFB) diode in a butterfly package that is directly current modulated by a short pulse diode driver made by Highland Technology (model T165). The seed source goes through two pre-amplifiers before entering the power amplifier. A fiber pigtailed isolator is placed in between each amplifier and after the seed source to block counter-propagating power. All components used in the experiment are low cost off-the-shelf parts such as pump combiner from Lightcomm, isolators from AFR, fused WDM from Gooch and Housego or circulator from AFW Technologies. The details of the amplifiers are presented in section 2.2 and 2.3.

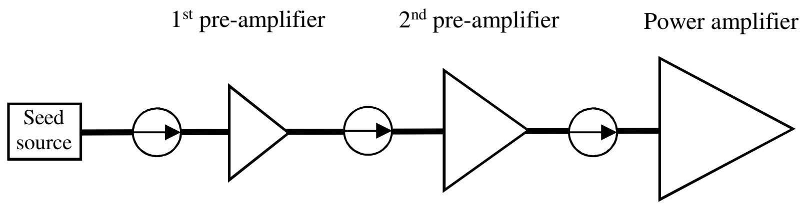


Figure 1. Overall schematic of the setup used in the experiment

All components and fibers were spliced together using standard cleaver and splicer available on the market (Fujikura FSM-100M and Vytran LDC-400). The temporal waveform was monitored using a 5GHz InGaAs photodetector (Thorlabs DET08CFC) and a 6 GHz oscilloscope (Agilent HP54855). Low power measurements were done with Fiber Optics InGaAs detector (Newport/ILX FPM-8220) and higher power measurement using a thermopile (Gentec UP19K-110F-H9). All spectrums were measured using an optical spectrum analyzer (Yokogawa AQ 6370C); when measuring the ASE power and signal power with the optical spectrum analyzer, the bandwidth was set to 1 nm to get a direction comparison of the ASE and signal power.

A 1ns/10kHz pulsewidth/repetition rate was used to obtain the 250 kW output peak power, but other settings such as 0.5ns/20kHz would have given similar results. Amplification results are sometimes shown in this publication with other pulsewidth/repetition rate settings for the purpose of optimization of a particular parameter in the amplifier chain.

2.2 First and Second pre-amplifier details

The details of the first pre-amplifier used are shown on Figure 2. Several configurations were tested, but the final setup used is a double pass configuration. The signal from the seed diode goes first through port 1 to 2 of the circulator. The signal is amplified a first time through 3 meters of CorActive's DCF-Yb-6/128S fiber using a multimode 915 nm pump diode injected in co-propagation with a 1+1→ 1 double cladding pump combiner. The Yb fiber has a core/cladding diameter of 6/128 µm with a cladding absorption of 0.55 dB/m at 915 nm. The core NA is 0.12. A cladding mode stripper (CMS) is used to absorb the residual pump light with a high index acrylate that glues a stripped portion of the fiber to a metal plate. A fiber Bragg Grating (FBG) reflects the signal light back in the amplifier for a second amplification in the backward direction. The bandwidth of the FBG is 2 nm large to filter out most of the amplified spontaneous emission (ASE) while giving room to fit the tolerances of the seed emission wavelength. The output of the FBG is angle cleaved to avoid any feedback that would reflect ASE. The backward amplified signal passes through the port 2 to 3 of the circulator to go toward the second pre-amplifier. A second isolator is placed to block the feedback from the second pre-amplifier. The 99.9%/0.1% coupler is optional and simply used to monitor and optimize the performance of the pre-amplifier online.

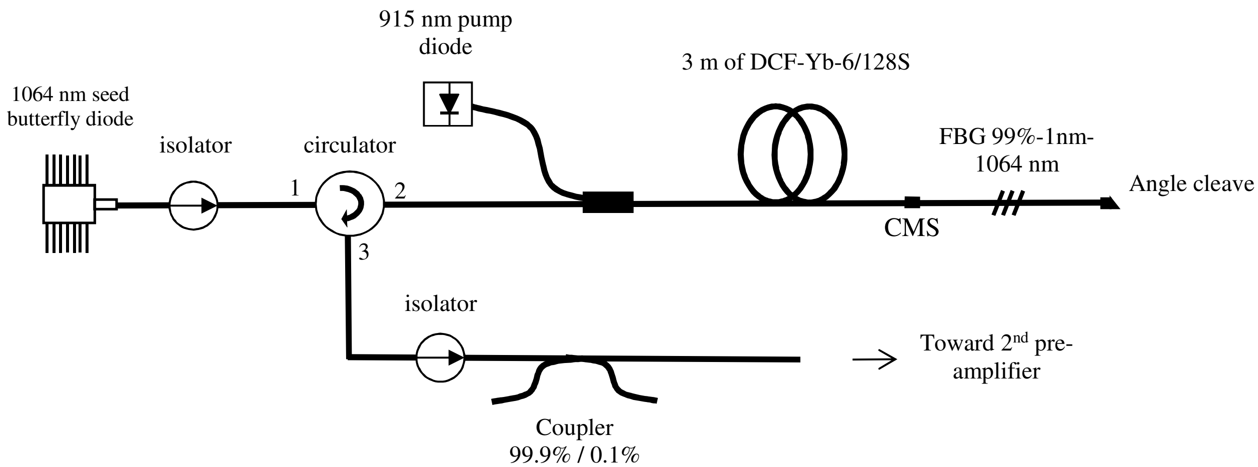


Figure 2. Detailed schematic of the first pre-amplifier used

Similar setups were tested when trying core pumping for the first pre-amplifier. First, instead of a 1+1→1 pump combiner, a 976/1064nm WDM was used, the 915 nm pump diode was replaced by a 300 mW singlemode pump diode at 976 nm, and the Yb fiber was replaced by a single cladding ytterbium fiber.

A single pass amplifier setup was also considered for the first pre-amplifier; the circulator and the FBG is removed such that only one amplification pass is created and sent directly to the second pre-amplifier after passing through an isolator. Thus, this first pre-amplifier setup has a very similar configuration than the second pre-amplifier shown on Figure 3.

The second pre-amplifier stage is done simply with a single pass forward double cladding amplifier as shown on Figure 3. Two meters of DCF-Yb-10/128E from CorActive was used. The fiber has a core/cladding diameter of 10/128 µm with a cladding pump absorption of 1.35 dB/m at 915 nm. The core NA is 0.085. A cladding mode stripper and an isolator were added before connecting the power amplifier. A monitoring tap coupler was also used after the second pre-amplifier to measure the power, pulsewidth and spectrum without disconnecting the power amplifier.

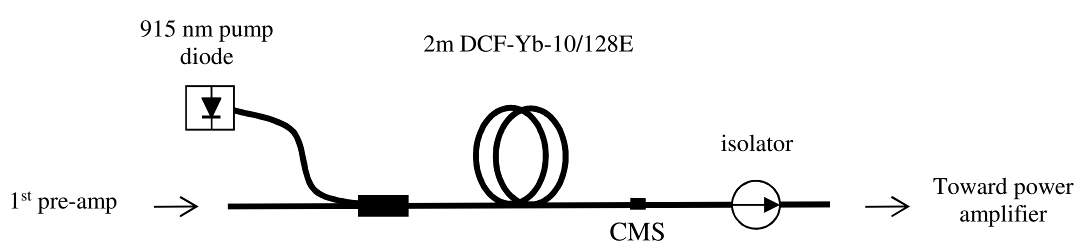


Figure 3. Detailed schematic of the second pre-amplifier

2.3 Power amplifier details

The power amplifier configuration is similar to the second pre-amplifier stage, except that a very short Yb length is needed and no delivery fiber is added to avoid non-linear effects as shown on Figure 4. A CMS is still used at the output to strip the residual pump light. To avoid facet damage and feedback, a 0.5 mm coreless fiber is spliced at the output with an 8 degree angle cleave; this expands the beam area by at least a factor of 5 before exiting the fiber, decreasing the power density at the fiber surface. Anti-reflection coating could have been added to eliminate the Fresnel loss.

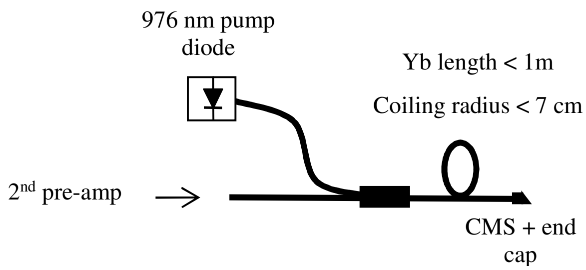


Figure 4. Detailed schematic of the power amplifier

The DCF-Yb-20/128P-FA and DCF-Yb-30/250P-FA phosphosilicate fibers from CorActive are used for the power amplifier. These fibers have a cladding absorption of 9 and 5.5 dB/m respectively at 915 nm, but when pumped at 975 nm, the small signal cladding absorption increases by a factor of 6, which explains why less than 1 m of fibers is needed to achieve a high peak power output. For phosphosilicate fibers, the peak absorption is exactly at 975 nm. However, only pump diodes at 976 nm were available, causing a 25% decrease in the small signal pump absorption. Volume Bragg grating wavelength locked pump diodes with bandwidth smaller than 1 nm from BWT Beijing were used to ensure that most of the pump power would be quickly absorbed by the narrow Yb absorption peak at 975 nm.

No delivery fiber was incorporated in the design: high peak power cannot be guided efficiently in a solid core optical fiber without generating non-linear effects. But this is not restrictive when using such amplifier design since the fibers used can be coiled to radii as small as 3 cm. Therefore it is possible to put the power amplifier Yb fiber alone in a small box that is placed directly at the application. The output of the power amplifier Yb fiber is then coupled directly to the output collimation optics; a free space isolator can be added if required. The electronics, pump diodes and pre-amplifiers are kept apart in the main laser module. The pump power and input signal are then brought from the main laser module to the remotely located small box containing the Yb fiber. This generates a free space beam directly where the final application needs it without added propagation lengths.

3. SEED OPERATION

3.1 Wavelength locking using a FBG

The natural emission wavelength of diodes can vary from one batch to another. When the exact emission wavelength of the seed diode is required, splicing a FBG after the diode is a simple solution[7]. The feedback of the FBG will lock the emission wavelength to the designed wavelength of the FBG. The feedback also contributes to the local enlargement of the spectral density of each mode of the Fabry-Perot resonator to decrease SBS[8], which is required to scale the output peak power. Figure 5 shows the output spectrum of a Fabry-Perot diode with a FBG spliced 20 cm away for different operating temporal pulsewidths. The FBG has a 5% reflectivity and 1 nm bandwidth at 1065 nm. It can readily be seen that as the pulsewidth gets shorter, the FBG becomes inefficient to lock the wavelength. The round trip time between the FBG and the diode is too long to get an efficient overlap of the reflected pulse with the initial pulse generation. The locking is not very efficient for pulsewidths below 10 ns. Putting the FBG closer to the diode will decrease the round trip time and enable shorter pulsewidth locking, but a limit in the minimum pulsewidth will be hit sooner or later.

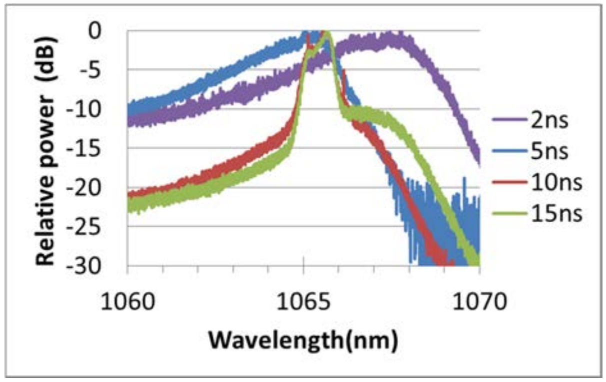
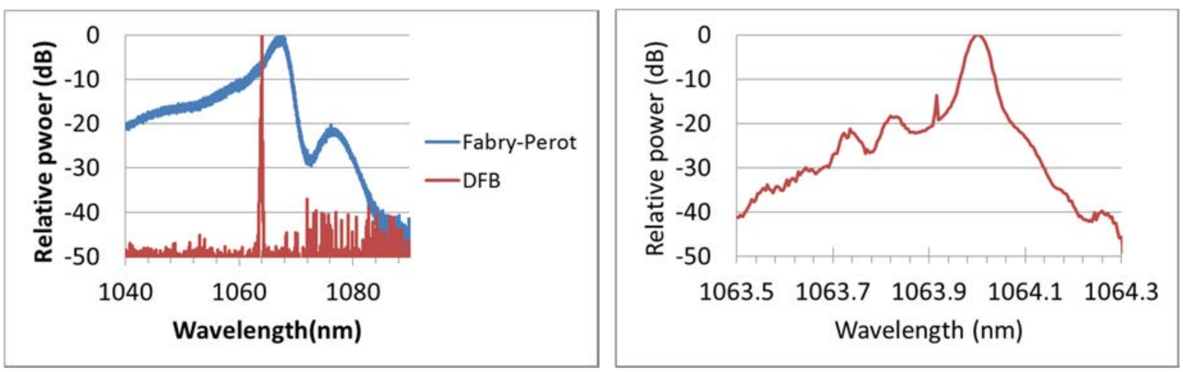


Figure 5. Output spectrum of a Fabry-Perot diode operated at different temporal pulsewidths when a 5% FBG with 1 nm bandwidth at 1065 nm is spliced 20 cm after the diode

3.2 Fabry-Perot vs DFB diode

Using a DFB diode is a solution to get a controlled emission wavelength at short pulsewidth. In such device, the grating occurs directly on the chip to control the emission wavelength. The output spectrum of a DFB diode compared to a Fabry-Perot at 2 ns pulsewidth as measured with an optical spectrum analyzer having 0.02 nm bandwidth resolution is shown on Figure 6 (a). Even for short pulse, the DFB device is able to maintain a 10 dB bandwidth of 0.07 nm in this case compared to more than 7 nm for the Fabry-Perot diode. A zoom on the spectrum of the DFB diode is shown on Figure 6 (b) showing that even at 20 dB, the total emission bandwidth is smaller than 0.2 nm. Such narrow linewidth is useful for applications such as frequency doubling using a non-linear crystal[9]. The trade-off of such a narrow linewidth however is a lower threshold for the onset of SBS as described further in section 5.3.



(a) (b)

Figure 6. (a) Output spectrum of a Fabry-Perot and DFB operated at 2 ns pulsewidth and (b) high resolution zoom on the spectrum of the DFB diode operated at 2 ns.

3.3 Average power and temporal oscillation

To obtain high peak power, it is required to operate the seed diode with small pulsewidths and moderate repetition rate to keep the overall duty cycle low such as setting the seed diode at 1ns/10kHz; this results in a very low average power at the seed level, sometimes in the order of a few µW. Figure 7 shows the measured seed average power as a function of repetition rate and pulsewidth for an applied peak current of 750 mA. The average power is basically directly proportional to the total duty cycle, which in return depends directly on the pulsewidth and repetition rate.

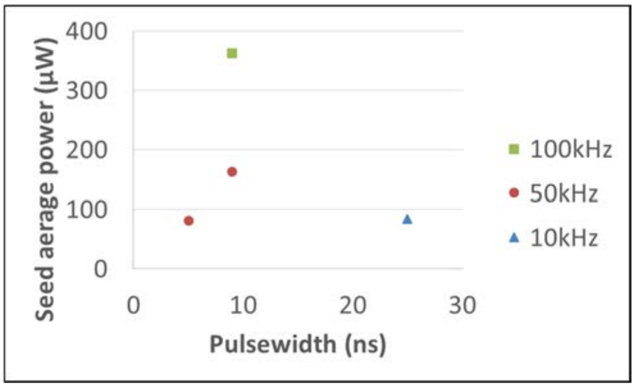


Figure 7. Measured seed average power as a function of repetition rate and pulsewidth for an applied peak current of 750 mA.

Applying a higher current is a possible solution to increase the average power as some diodes are rated at more than 2A peak current without risk of damage. However, due to the pulsed driver circuitry, unwanted oscillations can occur in the temporal waveform. A trade-off must then be found between the applied current and desired output waveform. It is also noted that to keep temporal oscillations as low as possible, the electrical pins of the diode must be as small as possible to reduce the inductance. A significant decrease in unwanted temporal oscillations is measured when going from 5 to 2 mm in pin length.

The way some manufacturers package the seed diodes may offer lower inductance and better control of the temporal waveform. Butterfly packages were used in this experiment, but other package such as the can type might be better suited for short pulse application. We could not test those assumptions during our experiments.

4. PRE-AMPLIFIER RESULTS AND OPTIMISATION

The average signal power from the seed diode can be as low as a few µW while the desired average output power is in the Watt range when high peak power is desired. This signal cannot be directly amplified in the power amplifier because the gain, in the order of 60 dB, will be too high. Such a high gain would cause self-pulsing of the ASE that would damage the amplifier. Typically a gain between 20 to 25 dB is a safe amplification level for a fiber amplifier. Therefore, two pre-amplifiers were used before entering the power amplifiers as shown on Figure 1.

It was observed that mitigation of ASE was quite challenging especially for the first pre-amplifier because of the very low input power, hence a careful optimization of the configuration is required. Many parameters can be optimized regarding the fiber choice and operating parameters of the pre-amplifiers; thus an in-house software[10] was used to quickly simulate the best amplifier configuration.

The simulation is based on a continuous wavelength (CW) regime, which is valid to predict the evolution of average power down to repetition rates of 5 kHz from our internal experience. All experiments are carried with repetition rate of 10 kHz and above, so the simulation can indicate the output average power and ASE level quite accurately. Non-linear effects are not included in the simulation; instead, the analytical formulae of Agrawal[3] are used to make sure a non-sense amplifier configuration is designed in term of stimulated Raman scattering and self-phase modulation. Then the fine-tuning of the non-linear effect mitigation could easily be done experimentally.

4.1 Theoretical optimization of the first pre-amplifier

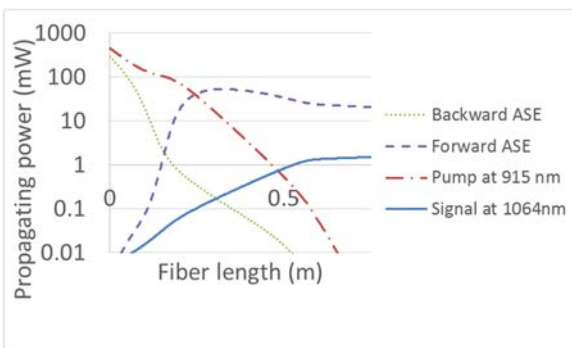
For all simulations of the first pre-amplifier, an input signal of 5 µW is used at 1064 nm for the seed power. This corresponds typically to the average power measured at 10 kHz repetition rate with 1 ns pulsewidth, which represents the worst case used in the experiment. This input signal is only simulated because any higher power would result in an easier amplification with lower ASE power generated. If a smaller pulsewidth were used, then a larger repetition rate would compensate the decrease in duty cycle to get the same average power of 5 µW. The output power aimed for the first pre-amplifier simulation is always 1.5 mW, which gives a safe gain of 25 dB and an interesting power level for the second pre-amplifier.

Since the required output power of the first pre-amplifier is less than a few mW, a single cladding amplifier is sufficient with typical pump diodes of 200 to 400 mW available on the market. Such an amplifier is first simulated and it is calculated that a double cladding amplifier is better suited for low input power signal at 1064 nm as described below. The starting parameters for the simulations were based on existing Yb fibers from CorActive.

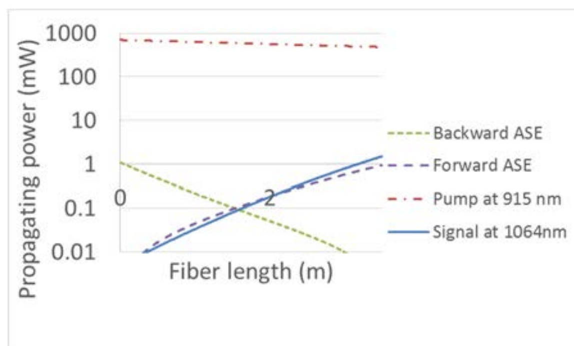
The single cladding amplifier is simulated using the CorActive Yb 401 product: a 5.5µm core diameter with 0.135NA and a core absorption of 140 dB/m. The ytterbium concentration is 0.75E26 ions/m using aluminosilicate cross-sections. The cross-section used for all simulations are given in reference [7]. As a starting point, 450 mW of singlemode pump power at 915 nm is used for the 0.75 m Yb fiber.

For the double-cladding amplifier simulation, the CorActive DCF-Yb-6/128S product was used: a core with 6 µm diameter and 0.12 NA with a 128 µm flat to flat octagonal diameter cladding. The cladding absorption at 915 nm is 0.5 dB/m, which gives an ytterbium concentration of 1.0E26 ions/m in the core using the aluminosilicate type cross-sections[8]. A 0.7 W of multimode cladding pump power at 915 nm is used for the 3.5m long double cladding Yb fiber

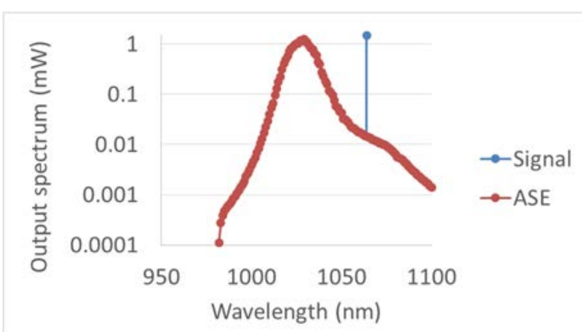
Figure 8 shows typical simulation results for (a) and (c) the single cladding fiber amplifier and (b) and (d) the double cladding fiber amplification. Figure 8 (a) and (b) present the evolutions of power and ASE in the fiber and the output spectrum is shown in Figure 8 (c) and (d). The pump power was adjusted in both cases to have an output signal of 1.5 mW. It is observed that for the same output signal, the total amount of generated ASE is much lower in the double cladding amplifier than in the single cladding amplifier. The very high inversion created by the core pumping of the single cladding amplifier generates a lot of inversion and thus ASE emission at 1030 nm. Most of the 450 mW pump power of the single cladding amplifier is absorbed and converted to ASE in both directions, particularly in the backward direction.



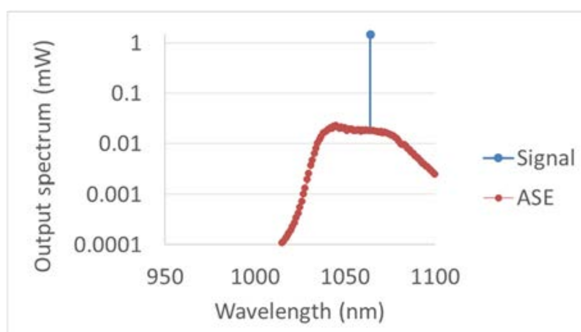
(a)



(b)



(c)



(d)

Figure 8. Typical simulation results in log scale when doing a 25 dB amplification gain of a 5 µW signal at 1064 nm. The left figures (a) and (c) show the results when using in 0.75m of 5µm core single cladding Yb fiber using 400 mW of pump power at 915 nm. Figure (b) and (d) on the right shows the results using 3.5m of 6/0.128µm core/cladding double cladding Yb fiber using 0.7W of cladding pump power at 915 nm. The two top figures (a) and (b) plot the evolution of propagating power in the fiber and the bottom figures (c) and (d) show the output spectrum in the forward direction.

The low inversion of the double cladding fiber generates low ASE in the 1040 to 1075 nm interval. Less than half of the 0.7 W pump power is absorbed in the double cladding fiber, but it is enough to generate a 1.5 mW output signal. Nevertheless, even if the total generated ASE is very different in both schemes, the ratio of output signal to the ASE at the signal wavelength is similar in both cases: computing the ASE generated in a 1 nm window at 1064 nm, the ratio between the signal and ASE at 1064 nm is 20 dB. Therefore, using a bandpass filter with 1 nm bandwidth will give 99% of the output power coming from the signal. If a true pulsed output power is desired, it is indeed important to monitor and minimize the CW background power from the ASE at the signal wavelength.

From these starting simulation parameters, we investigated if it was possible to decrease the background ASE at the signal wavelength to get a ratio higher than 20 dB. Self-pulsing of the ASE can also occur when the generation of ASE is too high. We thus tried to optimize the amplifier to decrease the total generated ASE in both directions. Table 1 summarizes the different configurations and optimization parameters tested to decrease the ASE power, for a single clad (SCF) and double cladding fiber (DCF) amplifier.

Table 1. Simulation results of different amplifier configurations and fiber optimization for the first pre-amplifier using a 5 μW signal at 1064 nm amplified with 25 dB gain using a single cladding (SCF) or double cladding fiber (DCF) pumped at 915 nm.

Configuration	**Output signal divided by ASE power at 1064 nm (dB)**		**Output generated ASE in both directions (mW)**	
	SCF	**DCF**	**SCF**	**DCF**
Forward pumping	20	20	310	2
Counter-pumping	20	20	310	2
Using phosphosilicate fiber	20	16	>600	7
Double pass scheme	9	17	60	0.2
Using larger or smaller NA	20	≤ 20	390	≥ 2
Using smaller or larger core	≤ 20	≤ 20	≥ 310	≥ 2
Using different fiber lengths or Yb concentration	≤ 20	≤ 20	≥ 295	≥ 2
Using confined Yb	≤ 20	28	≥ 310	0.5

As shown in Table 1, a standard forward pumping typically gives 20 dB signal to ASE ratio at 1064 nm, but the single cladding fiber amplifier generates much more ASE than the double cladding fiber. It can be noted that the data shown on the first line come from the simulation results of Figure 8. The ASE generation in the counter-pumping configuration is similar to the forward pumping case. By using a phosphosilicate fiber, the ASE generated is worst compared to the standard aluminosilicate fiber because the emission spectrum is shifted down further away from the signal wavelength due to the change in cross-sections. The double pass scheme (as shown in

Figure **2**) decreases significantly the total generated ASE because the gain in each pass is lower. However, the ratio at the signal wavelength is also decreased because the FBG also reflects the forward ASE at 1064 nm back in the backward pass, which adds to the ASE generated by the backward amplification gain. Thus, this scheme will significantly decrease the self-pulsing of the generated ASE, but a higher ASE CW background would occur at the signal wavelength. Changing the core diameter, NA or both did not improve the amplifier output as similar or higher amount of ASE is generated. The optimum core parameter occurs typically when the core is designed to be close to the cut-off of LP_{01} and LP_{11} mode (normalized frequency of 2.405), which is the case for the fibers with the starting parameters chosen for the simulation. Changing the Yb concentration and fiber length did not improve the amplifier output; a very small decrease of the generated ASE is however observed in the SCF case if a longer Yb fiber length is used due to the reabsorption at 1030 nm of the unpumped fiber.

The only situation where a significant improvement in performance is obtained is when the Yb is confined in the center of the core of a double cladding fiber. An extinction of 28 dB at the signal wavelength is simulated with respect to the ASE at 1064 nm when confining the Yb to a diameter of 3 μm within a 6 μm core diameter for instance; the generated

ASE is divided by 4 compared to the reference case. This improvement is not achieved in a single cladding fiber as the overlap of all the pump, ASE and signal powers is affected by the confinement. In a double cladding fiber, the pump power overlap depends simply on the area of the cladding and the Yb doping concentration and is decoupled from the signal and ASE.

Two popular pump wavelengths in ytterbium fibers are 915 nm and 976 nm to offer a loose tolerance on the pump wavelength fluctuation and to maximize the pump absorption, respectively. Two commonly used signal wavelengths are 1064 nm and 1030 nm because Yb doped silica fibers offer good gain in these regions[11]. Simulations are carried to compare those 4 wavelengths. The same basic forward scheme (shown in Figure 1) is used to do the comparison. When simulations are done with 976 nm pumping, the fiber length is reduced to get a similar amplification under the same input pump power. Table **1**Table 2 summarizes the simulations results for these mentioned wavelengths.

Table 2. Simulation results for the first pre-amplifier in forward pumping using a 5 μW signal amplified with 25 dB gain using a single cladding or double cladding fiber for two common signal and pump wavelengths.

Signal wavelength (nm)	**Pump wavelength (nm)**	**Output signal divided by ASE power at 1064 nm (dB)**		**Output generated ASE in both directions (mW)**	
		SCF	**DCF**	**SCF**	**DCF**
1064	915	20	20	310	2.0
1064	976	20	20	80	14
1030	915	20	16	25	13
1030	976	20	20	1.3	1.1

For the SCF amplifier, it is observed from Table 2 that lower ASE is generated with 976 nm pumping compared to 915nm pumping. In fact, the 976 nm pump is poorly absorbed in the SCF: the Yb absorption is so high that the pump absorption is bleached due to the equal emission and absorption cross-section at this wavelength. So the pump power is absorbed more slowly and allows the amplification of the signal before the onset of ASE. However, if the fiber length is increased, more pump power is absorbed and converted to ASE power without necessarily gaining more signal. The advantage of the 976 nm pump is then lost and therefore resembles the case of 915 nm pumping. Hence, the fiber length optimization is critical when core pumping at 976 nm is done. The 1030 nm signal wavelength also generates less ASE in the SCF amplifier because this wavelength is better amplified under the high inversion reached with the high pump density. The signal-to-ASE ratio at the signal wavelength is always the same whatever the wavelength used. So the optimization only allows reducing self-pulsing of the ASE but not the background CW ASE power at the signal wavelength.

For the DCF amplifier, pumping at 976 nm increases the total amount of generated ASE for a signal at 1064 nm because the Yb ions are more inverted and increase the gain of the ASE at shorter wavelength. But if the signal is changed to 1030 nm, then the amount of generated ASE is much lower with the 976 nm pump. Using a 915 nm pump with a 1030 nm signal is inefficient due to the low inversion reached; this is the only case where the signal to ASE ratio is lower at the signal wavelength.

4.2 Experimental results of the first pre-amplifier

The single cladding amplifier was experimentally tested with a pump wavelength of 976 nm using Yb 401 fiber and the 1064 nm of the seed. A wavelength division multiplexing fused coupler was used to couple the 976 nm pump with the 1064 nm signal in the Yb fiber. As expected, a great amount of ASE was generated at shorter wavelength. The ratio of the peak ASE power to the signal power was around 5 dB at the mW level output. A bandpass filter could get rid of most of the ASE, but another approach was tried by adding a length of CorActive SCF-Yb-550-4/125-19 fiber after the amplifier to absorb the ASE at 1030 nm. As described in the fiber product name, this product has a core diameter of 4 μm with 0.19 NA and a core absorption of 550 dB/m at 915 nm. An unpumped Yb fiber naturally absorbs the shorter wavelength faster, thus the ASE generated in our case. The results on Figure 9 show that the ASE decreases quickly with the length of the added Yb fiber. After 1 meter, the signal to ASE ratio is greater than 20 dB. The SCF-Yb-550-4/125-19 was chosen to reabsorb the ASE because of its phosphosilicate nature as it has greater absorption at shorter wavelength than aluminosilicate fibers. It can be noted that the SCF-Yb-550-4/125-19 fiber was also tested to do the amplification. As predicted by the simulation, the ASE power was higher compared to the Yb 401 since the latter is an aluminosilicate type fiber.

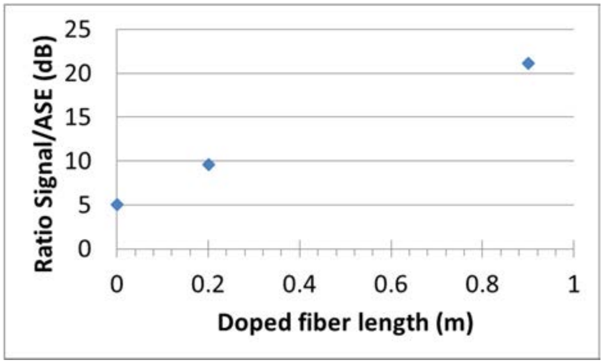


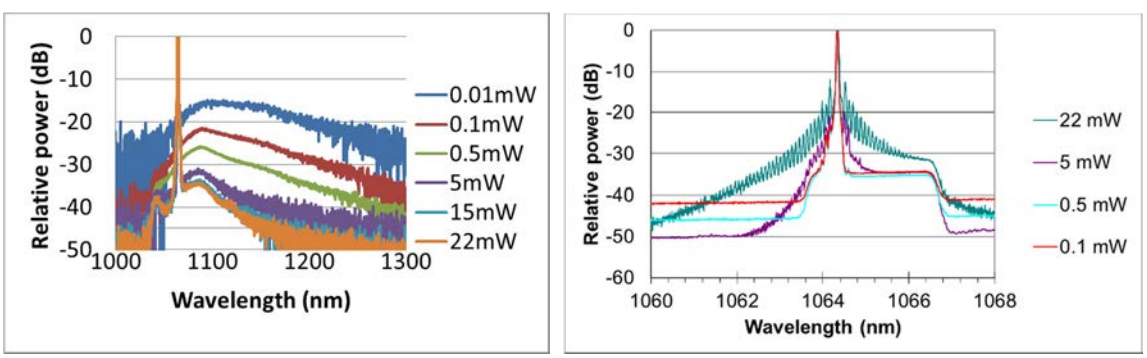
Figure 9. Ratio of the signal to the peak ASE power measured as a function of the length of the Yb fiber placed after the first pre-amplifier to absorb the ASE at shorter wavelength.

To further minimize the generated ASE and avoid the use of bandpass filter of reabsorbing Yb fiber, the double-pass configuration was used as previously described on

Figure **2**. First, the single cladding amplifier was used with the 976 nm pump and Yb 401 fiber. Amplification to the mW level could be easily achieved with 25 to 30 dB extinction ratio with the peak ASE power. But the ASE in the amplifier starts to self-pulse at 0.8 mW output even when using a high duty cycle of 100 kHz repetition rate and 9 ns pulsewidth from the seed. The insertion losses of the components of the double pass configuration adds up to 10 dB considering the isolators, circulator and couplers used; thus the required signal gain gets very high and increased the measured self-pulsing.

To further decrease ASE and avoid its self-pulsing, a double-cladding fiber was inserted in the double pass scheme as exactly described on

Figure **2**. The results of the first pre-amplifier at 50 kHz repetition rate and 5 ns pulsewidth are shown on Figure 10. On Figure 10 (a), the overall signal to ASE ratio is shown. As typical of double pass amplifier, the increased gain improves the signal to ASE ratio because the gain of the first pass improves the saturation of the amplifier for the reverse amplification pass. We can see that the output ASE is shifted toward the longer wavelength which is typical of lower inversion reached in DCF fiber pumped at 915 nm. Figure 10 (a) also shows no sign of stimulated Raman scattering in the amplifier. The signal to ASE ratio was higher than the simulated 20 dB because of the higher input signal of 80 µW used in this experiment.



(a) (b)

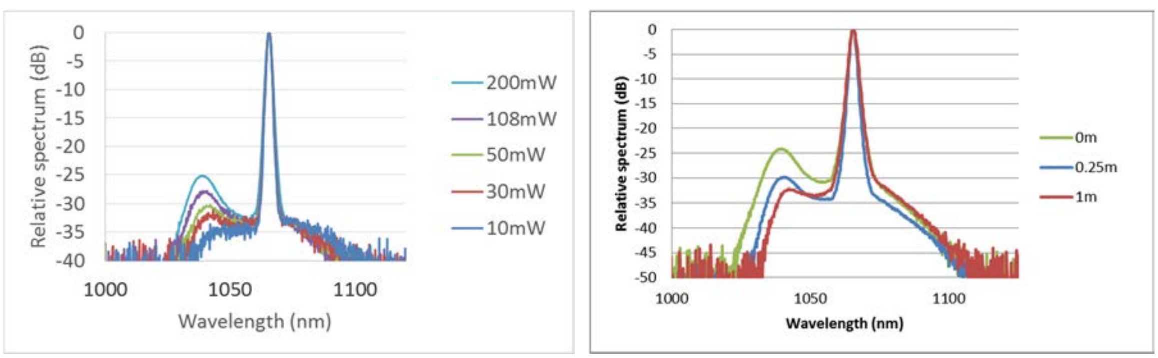
Figure 10. Spectrum measured at the output of the first pre-amplifier for different output average power at 50 kHz repetition rate and 5 ns pulsewidth. (a) Overall spectrum showing the ASE rejection (b) zoom near the signal at high resolution showing the onset of non-linear effects

Figure 10 (b) shows a zoomed graph of the spectrum of the same pre-amplifier with a much smaller resolution bandwidth of the optical spectrum analyzer. First, the bandwidth of the FBG used in the double pass scheme rests between 1063.5 to 1066.5 nm. The onset of four wave mixing and self-phase modulation are at around 5 mW output average power. The non-linear effects become evident at 22 mW output power. Similar behavior was measured using the Fabry-Perot or DFB seed diode. Therefore, this exact amplifier would need to be operated at an average power output less than 5 mW to minimize non-linear effects, which corresponds to 25 W peak power. However, the fiber length could be drastically reduced to minimize nonlinear effects if higher peak power is required without added non-linear effects. A simple pass scheme should be sufficient to get good ASE suppression with the DCF fiber, the monitoring coupler could be removed and the fiber length of each component could be cut by several meters; all those actions would reduce the propagation fiber length by at least a factor of 4 and thus scaling by the same amount the non-linear effect threshold.

4.3 Second pre-amplifier results

The second pre-amplifier was much more straightforward to accomplish. The input signal coming from the previous amplifier is already in the mW level, which makes the ASE management easier. To get a 25 dB amplification, the second pre-amplifier needs to amplify the signal to a few hundred mW of average power. As described in section 2.2, this is achieved by using 2 meters of CorActive DCF-Yb-10/128E fiber pumped at 915 nm. This only gives a total pump absorption of 2.7 dB at 915 nm, but since the required output signal is low, only a few Watt of pump power is enough to reach the desired output power with such short fiber length while minimizing non-linear effects.

Figure 11 shows typical results of the second pre-amplifier operating at 50 kHz repetition rate and 7.5 ns pulsewidth. Figure 11 (a) shows the output spectrum as a function of the output power. The extinction of ASE at 1064 nm stays constant with respect to the signal power, but ASE at 1040 nm starts to grow. A simulation for this amplifier shows that the ASE generated is not lower when using a 1030 nm signal. The generated ASE can be re-absorbed by using longer ytterbium fiber length as shown on Figure 11(b). This ASE absorption is maximized by having the added length unpumped by putting a cladding mode stripper between the amplifying Yb fiber and the re-absorbing Yb fiber. Another option would be to use a bandpass filter to get rid of all the ASE outside the signal amplification band.



(a) (b)

Figure 11. Spectrum measured at the output of the second pre-amplifier at 50 kHz repetition rate and 7.5 ns pulsewidth (a) for different average output power and (b) as a function of added unpumped Yb length to reabsorb the ASE at 1040 nm.

Even if it can sometimes be hardly seen on the pre-amplifier results, its operation conditions can impact the power amplifier result such as its output average power. For instance, Figure 12 shows the spectrum of the power amplifier at 125 kW peak power as a function of two different average powers coming from the pre-amplifier. The seed diode was operated in this case at 2ns/10kHz. At 150 mW input average power, the onset of stimulated Raman scattering (SRS) at 1116 nm is obvious compared to 100 mW. This added SRS is barely present at the output of the pre-amplifier measured alone even at 150 mW. In this case, it was better to bring more amplification to the last stage to minimize non-linear effects by tuning the output of one amplifier with respect to the upstream pre-amplifiers. This can be easily done online with the tap couplers between each amplifier stage, which can then be removed when non-linear effects need to be further reduced.

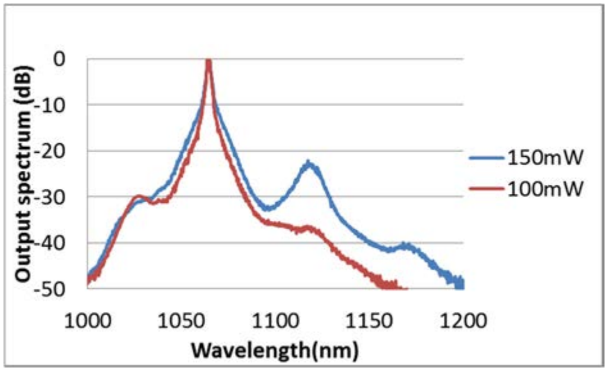


Figure 12. Spectrum of the power amplifier at 125 kW peak power as a function of two different pre-amplifier average powers of 100 and 150 mW.

If non-linear effects need to be further mitigated during the second pre-amplification, a larger core Yb fiber can be used such as a 20 µm diameter while still using a 128 µm cladding. This can double the mode area and cut the Yb fiber length in half due to the higher cladding absorption; a mostly singlemode output can still be obtained. Using simulations, the higher absorption will shift the gain toward the 1030 nm, so the trade-off is increased ASE when amplifying a signal at 1064 nm. A 1030 nm signal will generate a lower total amount of ASE, but the ASE at the signal wavelength will be the same for a 1030 nm or 1064 nm seed wavelength; so the use of a bandpass filter at the signal wavelength will result in the same amount of output ASE after the pre-amplifier. However, for a 1030 nm signal, the bandpass could be omitted since the total amount of forward ASE can be less than 0.5% of the signal power when amplifying for instance a 1 mW signal up to 300 mW at 1030 nm in 1 meter of a 20/128 double cladding Yb aluminosilicate fiber co-pumped at 915 nm. The same amplification using a 1064 nm signal will give forward ASE that amounts to 8% of the total output power; most of the generated ASE is around 1030 nm.

5. POWER AMPLIFIER RESULTS AND OPTIMISATION

The power amplifier was done using very short section of a highly doped phosphosilicate fiber pumped around 975 nm as described in section 2.3. Such a regime creates high inversion of the Yb doped fiber and pump bleaching; the pump absorption optimization is first discussed in section 5.1. Counter-pumping vs co-pumping is discussed in section 5.2 and finally the power amplification results are presented in section 5.3.

5.1 Pump absorption optimization

In double cladding fiber amplification, the cladding pump absorption is roughly equal to the Yb absorption in the core scaled by the core/cladding area. But our measured efficiencies as a function of fiber length clearly diverge from this rule. The cladding absorption of the DCF-Yb-20/128P-FA and DCF-Yb-30/250P-FA fibers are respectively 48 dB/m and 29 dB /m at 976 nm. So an effective pump absorption of 10 dB should occur for a fiber length of less than a third of a meter when pumped at 976 nm, which should give an efficient amplification of above 60%. Figure 13 shows the slope efficiency results obtained during the experiment: efficient amplification above 60% occurs for fiber length longer than 0.6 m, which is twice than expected from the small signal absorption.

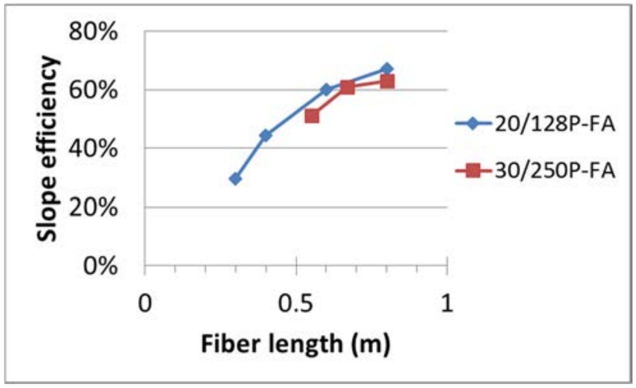
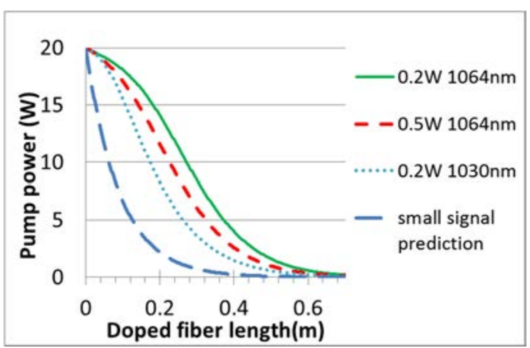
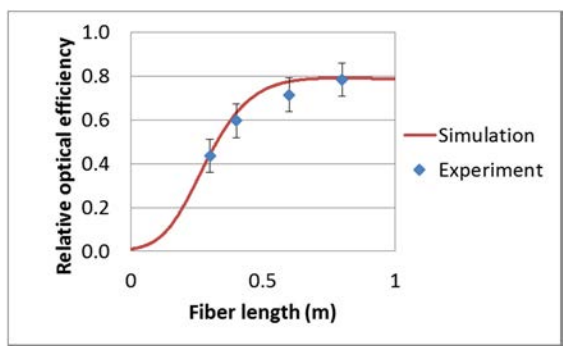


Figure 13. 1064 nm slope efficiency measured as a function of fiber length for the DCF-Yb-20/128P-FA and DCF-Yb-30/250P-FA when pumped at 976 nm.

The case of the DCF-Yb-20/128P-FA was simulated as shown on Figure 14. Figure 14 (a) shows that the pump absorption occurs on a much longer length than predicted by the small signal absorption. In other words, the real pump absorption is lower than the core Yb absorption scaled by the core/cladding area. This occurs since even though a double cladding fiber is used, the Yb inversion is high enough to bleach the pump absorption. This behavior is commonly met in core pump single cladding amplifier. Figure 14 (a) also shows that the pump absorption varies depending on the input signal used. A higher input signal power depopulates more the upper level of the Yb and increases the pump absorption. Using a 1030 nm signal is still a better option to improve the pump absorption because this wavelength is more absorbed by the Yb atoms and depopulates better the upper level. This can be readily be seen by the shape of the typical Yb absorption cross-sections[8]. Therefore a shorter signal wavelength and higher input power help shorten the fiber length, which then reduces non-linear effects. This can be achieved depending on the optimization and design choices made on the pre-amplifiers.





(a) (b)

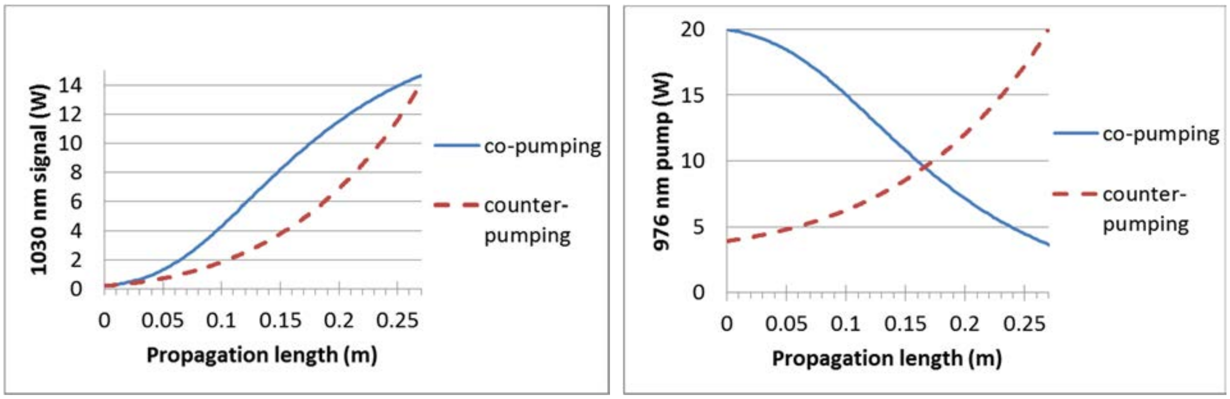
Figure 14. Using the DCF-Yb-20/128P-FA pumped with 20W of power at 976 nm, (a) simulation of the pump power evolution for different input signal power and wavelength; (b) comparison between the simulation and experimental results for the evolution of the relative optical efficiency as a function of fiber length

Figure 14 (b) shows that the simulation of relative efficiency as a function of fiber length fits well with the experimental results obtained with the DCF-Yb-20/128P-FA. This assures the pump absorption prediction of the simulations regarding the input power and wavelength used to maximize the pump absorption.

Higher fiber absorption typically decreases the fiber length used. However, in these very high inversion cases, the advantage is not directly proportional. For instance, drawing a preform to a 40/128 µm core/cladding diameter instead of 20/128 µm (as per the DCF-Yb-20/128P-FA) would increase the small signal cladding absorption by a factor of 4, but simulations shows that the reduction in fiber length would increase it just by a factor of 2 when pumped with 20W of power at 976 nm. This also explains why the length difference between the DCF-Yb-20/128P-FA and DCF-Yb-30/250P-FA is small (as seen on Figure 13), even if the pump absorption is quite different.

5.2 Co and counter-pumping comparison

Counter-pumping typically decreases non-linear effects since the signal is amplified more at the end of the gain fiber, thus high peak power propagates through a shorter fiber length[3]. The difference can be seen on Figure 15 (a) where the simulation of the propagating signal is run when co or counter-pumping 27 cm of DCF-Yb-20/128P-FA with 20W of power at 976 nm. The input signal is 0.2 W at 1030 nm. The length of 27 cm was chosen to give exactly 70% of conversion efficiency. Figure 15 (b) shows the evolution of the pump power in both pumping scheme; it can be seen that practically the same amount of pump power is absorbed in co or counter-pumping.



(a) (b)

Figure 15. Simulation of the propagating power when pumping 0.27 m of DCF-Yb-20/128P-FA with 20W of pump power at 976 nm when injecting an input signal of 0.2 W at 1030 nm: evolution of (a) signal power and (b) pump power

The generation of non-linear effects is proportional to the propagation length of the signal in the fiber. But since the signal power varies during the amplification, a concept of effective length[3,12] L_{eff} can be used. The effective length gives an equivalent propagation length of the signal at constant power in the amplifier as calculated with equation (1) below, where $P(z)$ is the evolution of the simulated signal along the fiber length L and P_{max} is the maximum signal power.

$$L_{eff} = \frac{1}{P_{\max}} \int_0^L P(z)dz \quad (1)$$

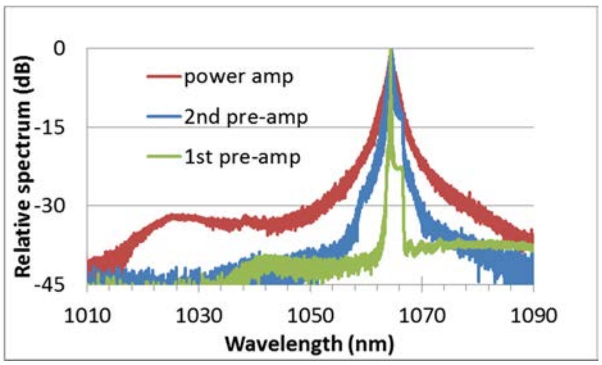
Using this equation, we calculate an effective length of 11.9 cm for the co-pumping vs 8.5 cm for the counter-pumping schemes simulated in Figure 15. This is a relative 30% difference in length, but the overall amplifier is so short that this effective length difference is less than 4 cm. Thus adding any standard pump combiner will erase all the gain of the counter-pumping scheme since it typically adds a few tens of cm. Counter-pumping would be interesting only if the pump coupling is done directly on the gain fiber without adding more than 3.4 cm of propagation fiber. Not adding any length with counter-pumping could be barely done only with free space coupling of the pump. But this takes off one of the main advantage of using fiber amplifier with its monolithic integration. Hence, counter-pumping is not much of an interest to decrease non-linear effects in highly doped very short length fiber amplifier.

Counter-pumping can get interesting mostly if a high conversion efficiency is required at the power amplifier stage. Then a longer length of Yb fiber can be added without much increase of effective length and non-linear effects. In the opposite, any increase in fiber length will be added directly to the effective length in the co-pumping scheme. A high conversion efficiency is interesting if a large output signal is required from the power amplifier not to waste too much pump power and decrease the thermal load on the cladding mode stripper.

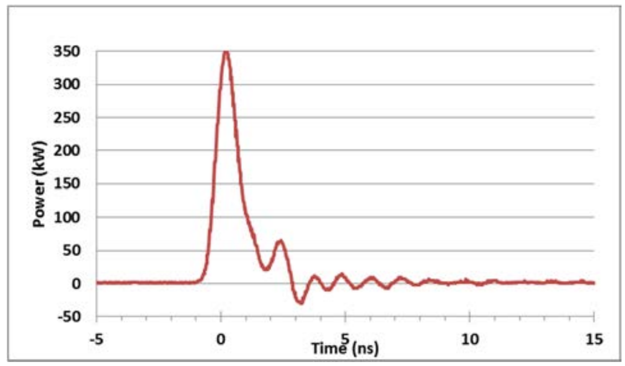
5.3 Power amplification results

By using 0.5 m of DCF-Yb-30/250P-FA operated at 4.4W average power at 10 kHz repetition rate and 1 ns pulsewidth, an output peak power of 350 kW was measured. The first pre-amplifier and second pre-amplifier were operated at 50W/1mW peak/average power and 5kW/100 mW peak/average power respectively. The results are shown on Figure 16. Some ripples are seen in the temporal waveform and are due to the seed diode driver itself. A peak power of 350kW was computed conservatively including those ripples. Furthermore, since we suspected some overshoots in the temporal detection when comparing different detector/oscilloscope setups, we reduced the achieved effective output peak power to be 250 kW.

Looking at the spectrum of Figure 16 (a), we can see that most of the spectral broadening at 15 dB bandwidth occurs from the second pre-amplifier; the power amplifier has practically the same output spectrum as measured at its input. A closer view on the spectrum reveals that this broadening is mainly due to the occurrence of four-wave mixing secondary modes. Therefore, further optimization of the second pre-amp such as removing the output monitoring coupler would remove most of the spectral broadening. The spectrum is not shown above 1090 nm, but no Stimulated Raman Scattering was measured around 1115 nm.



(a)

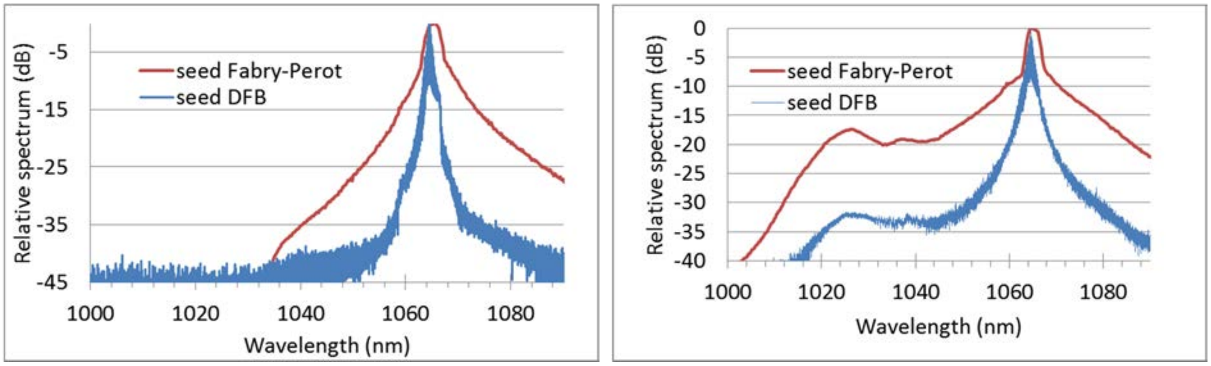


(b)

Figure 16. When operating the DFB seed at 10 kHz and 1 ns pulsewidth (a) output spectrum measured after each amplifier stage and (b) output temporal waveform measured after the power amplifier

In this experimental test, the limiting factor is the Stimulated Brillouin Scattering (SBS): backward spikes occurred when reaching 350 kW output peak power. This was not due to self-pulsing from the ASE since no SBS was detected when using a Fabry-Perot instead of a DFB seed diode, which gives a larger effective linewidth that decreases SBS[3]. SBS decreases rapidly with pulsewidth below 10 ns[13] because of the acoustical phonon lifetime that generates SBS[3]. A simple solution to increase the SBS threshold is to decrease the seed pulsewidth and then, the repetition rate can be increased to get the same input average power to facilitate the ASE and non-linear effects mitigation during the pre-amplifications. For instance, similar results than Figure 16 are expected at 20 kHz repetition rate and 0.5 ns pulsewidth, but with a higher SBS threshold. We expect that peak power of more than 500 kW could be obtained using a smaller pulsewidth and properly optimizing each amplifier stage. There is still room for using larger core fiber at the power amplifier while preserving a good beam quality. Tapering the input of the Yb fiber can be done to adiabatically inject the fundamental mode from a spliced singlemode or few moded input injection fibers.

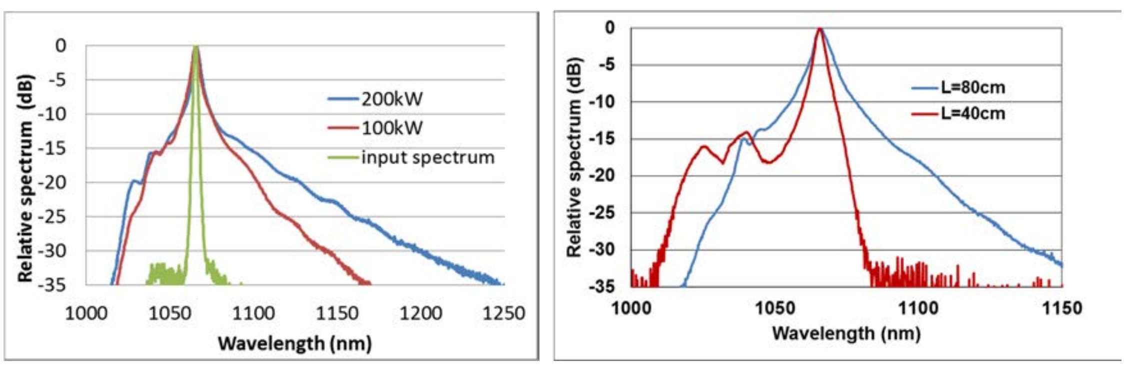
Figure 17 (a) shows the output spectrum of the second pre-amplifier at 5 kW output peak power and Figure 17 (b) shows the power amplifier at 250 kW peak power by using a DFB or Fabry-Perot diode operated at 10 kHz repetition rate and 2 ns pulsewidth. The Fabry-Perot diode has a much larger effective spectrum than the DFB diode, so it suffers more from self-phase modulation during the amplification. No sign of stimulated Raman scattering was measured in both cases, so the dominant non-linear effect is solely self-phase modulation. In the case of the DFB seed diode, the dominant effect is four-wave mixing since narrow secondary peaks appeared during the amplification.



(a) (b)

Figure 17. Output spectrum at 10 kHz repetition rate and 2 ns pulsewidth using a DFB feedback or Fabry-Perot (FP) seed diode after (a) the second pre-amplifier operated at 5 kW peak power and (b) the power amplifier operated t 250 kW peak power

Figure 18 shows the output spectrum of the DCF-Yb-20/128P-FA operated at high peak power with the Fabry-Perot seed diode at 25 kHz repetition rate and 5 ns pulsewidth. Figure 18 (a) shows that at 100 kW, the power amplifier suffers from self-phase modulation (SPM) with a 10 dB bandwidth of 20 nm. If the output power is increased to 200 kW, no more gain occurs at the signal wavelength around 1064 nm, only new wavelengths are created in the 1100 to 1250 nm region due to SPM again. So the power amplifier is operated at its limit at 100 kW if in-band power is desired. A solution to decrease non-linear effects such as SPM is to decrease the fiber length. Figure 18 (b) shows the same DCF-Yb-20/128P-FA fiber operated at 100 kW with two different fibers lengths of 40 and 80 cm. SPM is significantly reduced, but because of the shorter fiber length, shorter wavelength around 1030 nm start to be favorably amplified, which explains the secondary peaks at lower wavelength for the 40 cm fiber length. A seed diode at 1030 nm would avoid such uneven amplification because it is naturally favored in the amplifier. A DFB seed would also eliminate those low wavelength peaks because its spectrum enlargement would not reach the 1030 nm window.



(a) (b)

Figure 18. (a) Output spectrum at 25 kHz repetition rate and 5 ns pulsewidth for (a) two different peak power using 80 cm of DCF-Yb-20/128P-FA and (b) at 100kW peak power for two different lengths of DCF-Yb-20/128P-FA using a Fabry-Perot seed diode

6. CONCLUSION

A directly current modulated fiber pigtailed seed diode was used to inject short pulses into the amplifiers at moderate repetition rates. A Fabry-Perot diode happens to have a large linewidth that could not be effectively locked under small pulsewidth using an external FBG. A DFB diode could directly generate a much narrower spectrum, however with the trade-off of higher SBS during the amplification, which can be mitigated by using a smaller pulsewidth. Oscillations in the pulse temporal waveform can be reduced by decreasing the peak current at the diode and avoiding additional inductance with short diodes pins.

The low average power in the μW range of the seed diode can make ASE mitigation in the first pre-amplifier challenging. Simulations show that the use of a confined double cladding fiber gives the lowest output ASE with a core normalized frequency close to the LP_{11} cut-off. Pumping at 915 nm gave the best ASE mitigation with a 1064 nm signal, while 976 nm pumping would be more useful in the case of a 1030 nm signal. More simulations show that core pumping, counter-pumping and different core parameters and Yb concentrations do not help regarding ASE mitigation. Using those simulations results, self-pulsing of the ASE in the first pre-amplifier was eliminated experimentally. Added unpumped Yb lengths or bandpass filters were used to further absorb ASE. Optimization of the fiber length, seed duty cycle and active mode area allow mitigation of nonlinear effects at the pre-amplifier stages.

The operation of short highly doped phosphosilicate fiber at the power amplifier stage causes pump bleaching even for double-cladding fibers; increasing the signal power and decreasing the signal wavelength could reduce this saturation effect. Simulations show that counter-pumping does not mitigate much non-linear effects in very short length amplifiers, the main advantage would mainly be an increase of the conversion efficiency. A 250 kW output peak power was realized using such a 3 stage monolithic solid core fiber amplifier setup. By using small fiber coiling radius, we avoided the use of delivery fiber which further mitigates nonlinear effects.

A 500 kW output is expected to be reached with a spectral width smaller than 0.2 nm by doing proper pre-amplifier optimizations and using larger solid core diameter fiber that still preserves good beam quality.

7. REFERENCES

[1] Overton, G., Nogee, A., Belforte D. A. and Holton, C., "Annual Laser Market Review & Forecast: Can laser markets trump a global slowdown?," LaserFocusWorld, (2016).

[2] Nikumb, S., Chen, Q., Li, C., Reshef, H., Zheng, H. Y., Qui, H., Low, D., "Precision glass machining, drilling and profile cutting by short pulse lasers," Thin Solid Films 477(1-2), 216-221 (2005).

[3] Agrawal, G. P., [Nonlinear Fiber Optics], Academic Press, San Diego, (2001).

[4] Morasse B., Chatigny S., Gagnon, É., Hovington, C., Martin, J.-P. and de Sandro, J.-P., "Low photodarkening single cladding ytterbium fibre amplifier," Proc. SPIE 6453, 64530H (2007).

[5] Di Teodoro, F., Brooks, C. D., "Multistage Yb-doped fiber amplifier generating megawatt peak-power, subnanosecond pulses," Opt. Letters. 30**,** 3299-3301 (2005).

[6] Dong, L., Peng, X., Li, J., "Leakage channel optical fibers with large effective area," JOSA B 24**,** 1689-1697 (2007).

[7] Yang, G., Smith, G. M., Davis, M. K., Loeber, D. A. S., Hu, M., Zah, C. and Bhat, R., "Highly reliable high-power 980-nm pump laser," IEEE Phot. Tech. Let. 16(11), 2403-2405 (2004).

[8] Morasse B., Chatigny S., Gagnon É, de Sandro, J.-P. and Desrosiers C., "Enhanced pulseshaping capabilities and reduction of non-linear effects in all-fiber MOPA pulsed system," Proc. SPIE 7195, 71951D (2009).

[9] Jacquemet, M., Goyat, E., Mugnier, A. and Pureur, D. "Small linewidth CW high power PM Yb-fiber laser around 1150 nm and yellow generation," Proc. SPIE 7195, 71950G (2009).

[10] Morasse, B., Chatigny, S. Hovington, C. and Piché, M., "Accurate Modeling and Experimental Validation of a Singlemode 4 Watt Output Power Double Cladding Erbium Ytterbium Fibre Amplifier," Conference OAA/COTA, JWB36 (2006).

[11] Pask, H. M., Carman R. J., Hanna, D. C., Tropper, A. C., Mackechnie, C. J. Barber, P. R. and Dawes J. M. "Ytterbium-doped silica fiber lasers: versatile sources for the 1-1.2 μm region," IEEE J. of Sel. Top. in Quantum Elec. 1(1), 2-13 (1995).

[12] Ramaswami, R. and Sivarajan, K., [Optical Networks — A Practical Perspective], Morgan Kaufmann Publishers, San Francisco, (1998).

[13] Desbiens, L., Roy, V., Deladurantaye, M., Taillon, Y., "On the SBS threshold of optical pulse shapes compensated for gain saturation," Proc. SPIE 8601, 86012V (2013).