kW Pulsed Nanosecond 1952 nm TDFL with Direct Modulation

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ABSTRACT

We present a kW level pulsed laser based on a master oscillator power amplifier (MOPA) configuration. The directly modulated single frequency laser at 1952 nm is pulsed in the nanosecond regime with 10 kHz to 2 MHz repetition rate frequency. The MOPA topology is based on a two stage amplifier using single clad Thulium-doped fiber: a pre-amplifier followed by a booster stage. We investigate the performance of this pulsed laser for two different fibers in the booster stage with different saturating energies. The direct modulation allows us to demonstrate more than 1 kW of output peak power over pulse repetition frequencies from 10 kHz to 500 kHz. For a pulse of 21 ns, we demonstrate energy of 12 µJ and 25 µJ for booster fiber saturating energies of 15 µJ and 30 µJ, respectively.

Keywords: Pulsed, nanosecond, direct modulation, MOPA, Thulium, 2 microns.

1. INTRODUCTION

Pulsed laser sources in the 2 µm region have attracted much attention for their applications in LIDAR, atmospheric sensing, pumping OPOs, and materials processing. Pulsed Thulium-doped fiber lasers (TDFL) operating in the nanosecond regime (<100 ns) have been demonstrated using gain switched cavities, Q-switched cavities, external modulation, or direct modulation. So far, the direct modulation of a semiconductor laser has attracted relatively little attention and only H. Shi et al. [1,2] have reported MOPA systems delivering more than 100 watts average. Although single-frequency lasers at 2 µm have made significant progress, their P_{out} remains moderate, between 1 and 10 mW. This limited output power represents a challenge in pulse mode where the average power is reduced by the duty cycle (20 to 30 dB), making the amplification harder. However, the benefit of a MOPA approach with direct modulation of the seed laser is a cost effective solution with a large flexibility in term of pulse parameters: pulse shape, pulse width (PW), pulse repetition frequency (PRF), and signal wavelength.

In this paper we demonstrate a two stage MOPA pulsed laser delivering more than 1 kW of output peak power over repetition rates from 10 kHz to 500 kHz with pulse widths between 21 ns and 6 ns. This two stage TDFL is based on a pre-amplifier delivering high signal gain followed by a booster stage providing high output peak power. We first describe the pulsed performance of the pre-amplifier, and then report the performance of a two stage amplifier using two different single clad TDF with different saturating energy values.

2. EXPERIMENTAL TDFL SETUP

The pulsed MOPA used is shown in Figure 1. It is composed of a single frequency seed laser at 1952 nm whose drive current is pulsed, followed by a two stage TDFA consisting of a pre-amplifier and a booster stage.

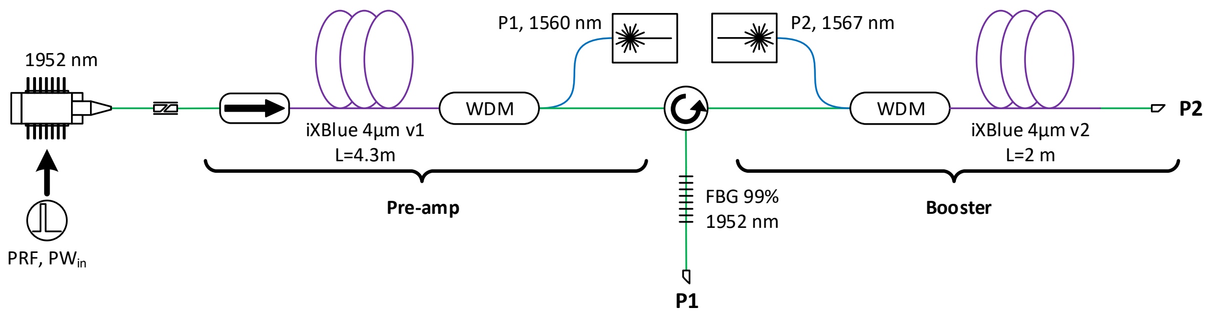

Figure 1: Topology of our pulsed two stage single clad TDFL.

In the CW regime, the seed laser delivers 2.6 mW at 1952 nm. In a pulsed regime, the combined bandwidth of the laser and the driver allows us to generate pulse widths between 6 ns and 21 ns with repetition frequencies from 10 kHz to 2 MHz. As an example, with a pulse width of 21 ns, the seed laser delivers -10.7 dBm for a PRF=2 MHz and only –33.9 dBm for a PRF of 10 kHz. Figure 2 shows the normalized output pulse shapes from the semiconductor laser. We observe the gain switch of the semiconductor cavity at the beginning of all three pulses. The pulse characteristics were recorded with a 12.5 GHz photodiode mounted on a 30 GHz oscilloscope.

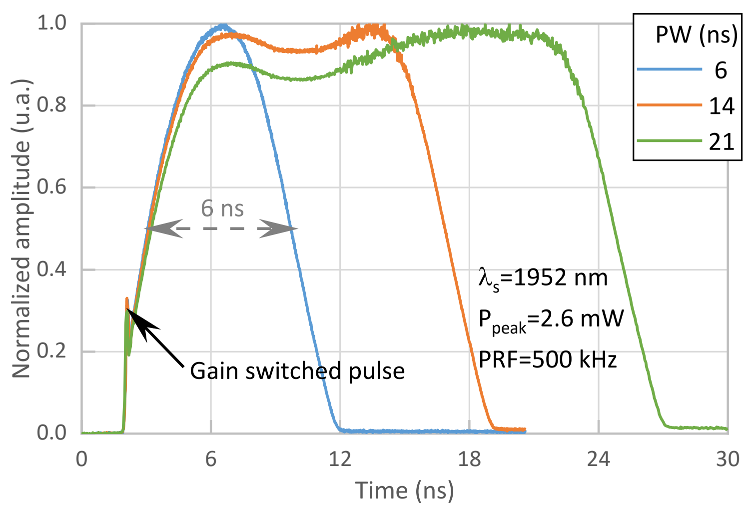

Figure 2: Output pulse shape for three pulse widths from the 1952 nm single frequency seed laser.

The two-stage amplifier is composed of a pre-amplifier followed by a power booster. The pre-amplifier was designed following the CW study [3], and it is based on a 4.3 m long iXBlue 4 µm v1 Thulium-doped fiber counter-pumped by a 1560 nm fiber laser. The counter-pumping topology was chosen because it provided a higher signal gain than the co-pumping configuration. A mid-stage 1 nm FBG filters the ASE from the pre-amplifier output to prevent saturation of the booster stage by the large ASE level from the pre-amplifier output. Two topologies were investigated for the booster stage, both designed using a CW study [4]. The first topology uses 2 m of iXBlue 4µm v2 while the second one uses 1.2 m of iXBlue 5µm. The two topologies investigated in the booster stage are based on a co-pumped configuration which allow us to decrease the output signal loss of the amplifier and also decrease the length of output passive fiber, which helps to lower the threshold of the onset of non-linearities. All the pumps of our TDFL were powered in a CW regime.

The characteristics of the different fibers used in this pulsed TDFL are summarized in Table 1, where $\alpha(\lambda)$ is the absorption parameter and $g^*(\lambda)$ is the gain parameter. The fundamental parameters were measured previously for the fibers [5]. The parameters listed are those needed to calculate the energy saturation (E_{sat}) at the signal wavelength of 1952 nm. The saturating energy (defined through Equation (1)) is a figure of merit used in the comparison of different fibers. A large saturating energy allows high output energy pulses before a pulse is subject to gain depletion, which results in a change of pulse shape. We note that two 4 µm core fibers out of the three have comparable saturating energy at the signal wavelength and so should provide comparable pulse output signal. The last one, the SCF 5µm, should provide the highest output energy out of the three selected fibers. The table also gives the maximum measured CW slope efficiency ($\eta_{o\text{-}o}$) using a 1567 nm fiber laser pump from our previous study [4].

Parameter	iXBlue single clad Thulium-doped fiber		
Reference	SCF 4μm v1	SCF 4μm v2	SCF 5μm
Core diameter, $2a_{core}$ (μm)	4	4.5	5.3
Numerical aperture, *NA* (u.a.)	0.27	0.26	0.17
Optical efficiency, $\eta_{o\text{-}o}$ (%)	57	70	53
Doping level, *N* ($\times10^{25}$ m^{-3})	12.3	7.1	25.6
α @ λ_s=1952 nm (dB.m^{-1})	1.55	1.12	4
g^* @ λ_s=1952 nm (dB.m^{-1})	43.8	31.6	80.1
E_{sat} @ λ_s=1952 nm (μJ)	15.1	15.2	29.7

Table 1: Energy saturation and characteristics of three different Thulium-doped fibers used in our pulsed TDFL.

$$E_{sat}(\lambda) = \frac{h.c.\pi.a_{core}^2}{\big(\alpha(\lambda) + g^*(\lambda)\big)\lambda} \quad (1)$$

3. PRE-AMPLIFIER PERFORMANCE

To test the performance of the pre-amplifier, we monitor the output pulses on port P1 of the setup shown in Figure 1. To perform our measurements, we detuned the seed to an operating wavelength of λ_s=1951 nm so that its wavelength was out of the reflection bandwidth of the FBG which was centered at 1952 nm.

This pre-amplifier was demonstrated to deliver high gain in a CW regime with up to 38 dB with a P_{in}=-20 dBm and a pump power P_{p1}=1 W. Figure 3 shows the signal gain versus the pump power for different pulse repetition frequencies. More than 35 dB gain is demonstrated, with the operation limited by the lasing in between pulses. We observe a decrease of the gain with an increase of the PRF, noticeable for PRF=2 MHz.

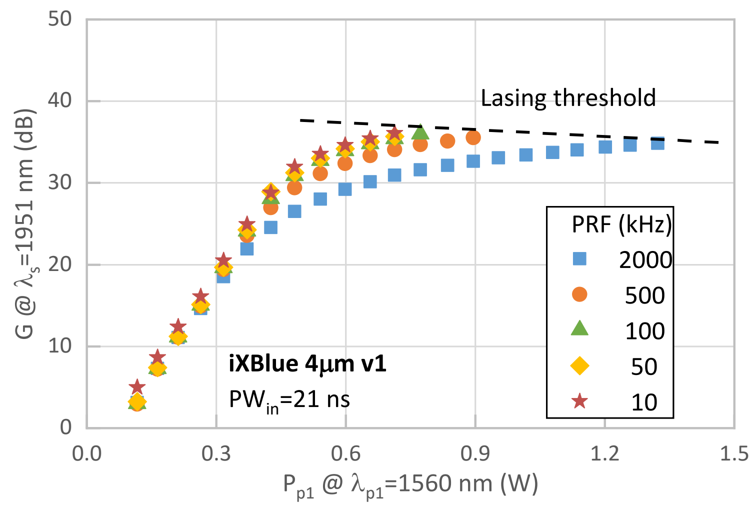

Figure 3: Pre-amplifier signal gain versus pump power for different repetition rate.

The pulse shapes were recorded as shown in Figure 4, where we show the output pulse shape for a PRF of 500 kHz and a pulse width of 21 ns at a pump power of 0.7 W. We note that the shape has not evolved compared to the shape displayed in Figure 2. The output pulse width was measured for all the tested conditions. Overall we found that the amplifier is not in a gain depletion regime. We also include in Figure 4 the Frantz-Nodvik calculation of the pulse shape. We note a good agreement with the pulse shape and a slightly lower amplitude for theory compared with experiment.

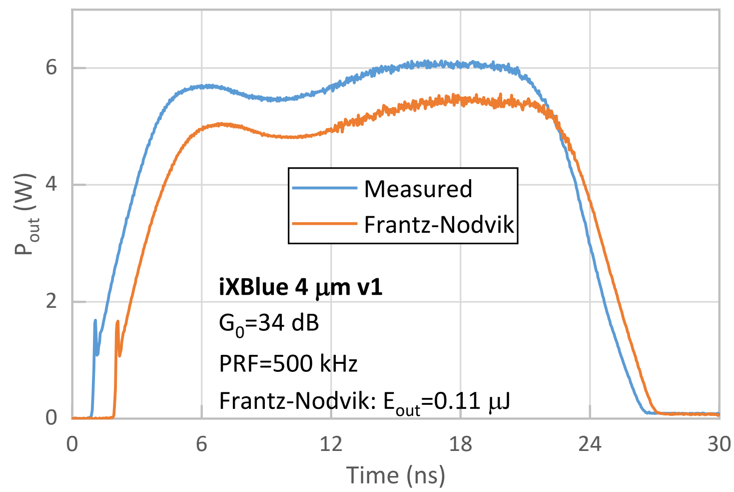

Figure 4: Output pulse shape from the pre-amplifier.

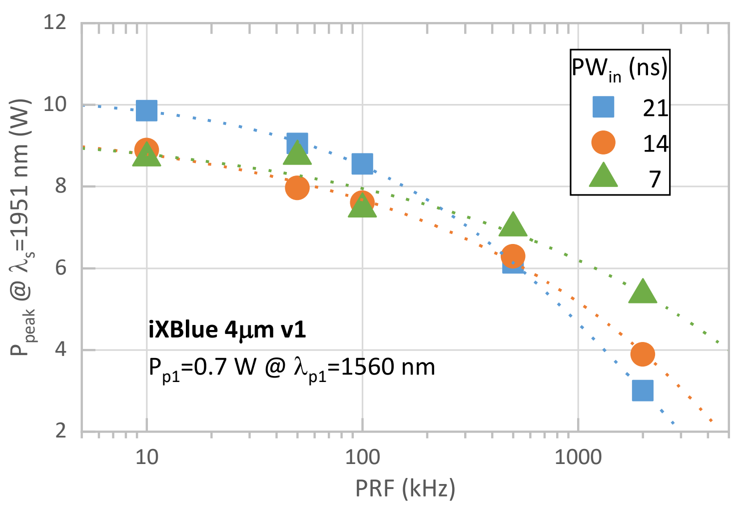

Figure 5: Peak power versus pulse repetition rate for different input pulse width.

Next, the normalized output spectrum of the amplifier was recorded and is shown for different PRF in Figure 6. We observe that the amount of ASE increases with decreasing PRF. The OSNR follows the same trend. The ratio of output signal power to total output power ($P_{out}(\lambda_s)/P_{out}$) is shown in the inset in Figure 6 versus PRF for input pulse widths of 6, 14, and 21 ns. We observe that, with the pulse width decreasing, the ratio of signal power to total power also decreases. This clearly shows that an ASE filter between the pre-amplifier and the booster stage is necessary to prevent excess ASE power from limiting the saturation of the booster stage. No ASE outside the FBG band was observed after the ASE filter.

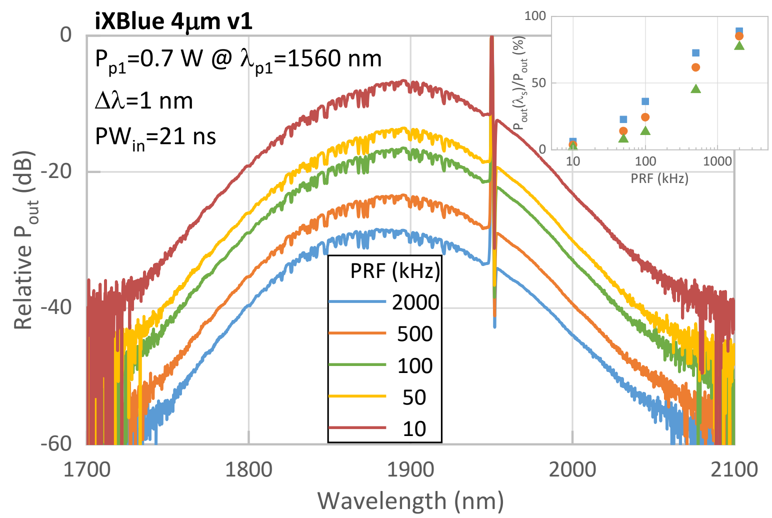

Figure 6: Output spectrum versus the pulse repetition rate for an input pulse width of 21 ns.

4. TWO STAGE PERFORMANCE

With the pre-amplifier pump power set to 0.7 W, we next monitored the output performance of the two stage amplifier on port P2. Three different topologies were investigated in the booster stage: 1) two topologies based on single clad TDF (iXBlue 4 µm v2 L=2 m, and iXBlue 5 µm L=1.2 m) pumped with an Er:Yb fiber laser, and 2) one topology based on a double clad TDF (iXBlue 6 µm L=4.8 m) co-pumped in the clad at 793 nm. The first configuration, with the booster active fiber based on iXBlue 4 µm v2, had an interstage signal loss of 4.5 dB (splice losses + component losses) whereas the two other configurations had losses of 5.5 dB.

We start by comparing the output peak power of the two stage amplifier for an input pulse width of 21 ns as shown in Figure 7 for both configurations. The pulse shape was taken in account in the calculation of the peak power. We observe that for both configurations we were able to deliver an output peak power greater than 1 kW for different pulse repetition frequency. At low PRF (<500 kHz), both configurations were limited by the onset of lasing on top of the ASE in between pulses. The iXBlue 5µm delivered up to 2.7 kW at 10 and 50 kHz, while the iXBlue 4µm v2 delivered up to 1.2 kW at 100 kHz. We note that at 500 kHz only the iXBlue 4µm v2 provided more than 1 kW of output peak power thanks to its better slope efficiency (70 % against 53 %). One way to overcome the onset of lasing limitation in both amplifiers would be to modulate the pump power, switching it off after the pulse and back on before the pulse to load the active fiber, allowing us to extract higher energies. These measured peak powers correspond to a maximum output energy of 13 µJ for the iXBlue 4µm v2 configuration and 29 µJ for the iXBlue 5µm configuration.

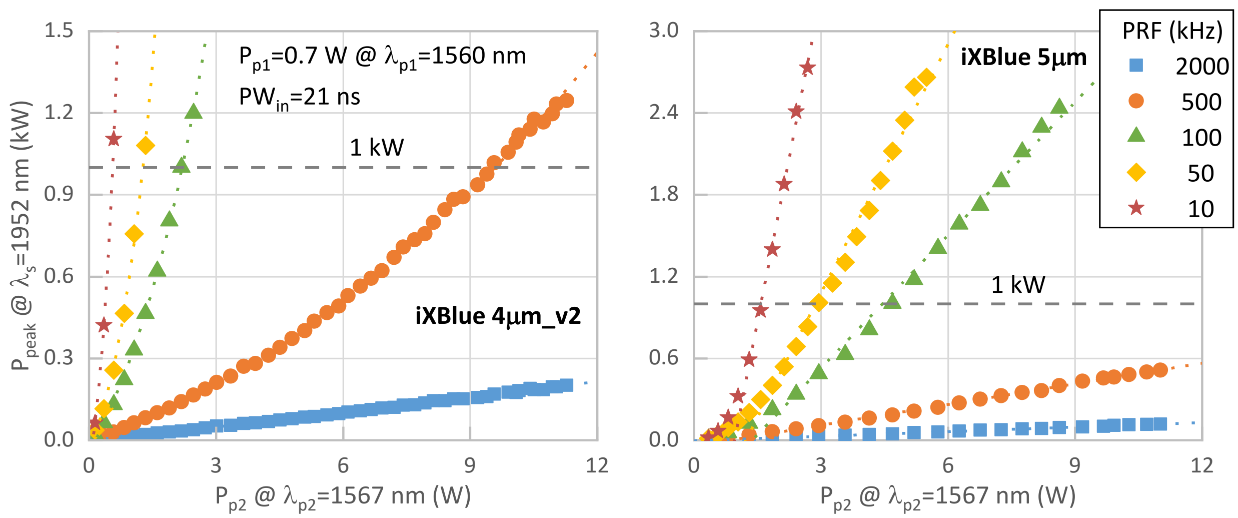

Figure 7: Output peak power as a function of the pump power for the iXBlue 4um_v2 (left) and the iXBlue 5um (right).

We then focused on a PRF of 500 kHz and an input pulse width of 21 ns. The pulse shapes were recorded and the output pulse shapes are displayed for three different signal gain levels with their respective Frantz-Nodvik simulations. Figure 8 shows the evolution of the pulse shape with the pump power increasing. As the pump increased, we observed a distortion of the pulse shape with a gain distributed mainly toward the beginning of the pulse. Comparing the output pulse shape from the two single clad configuration we note that the output pulse shape from the iXBlue 5μm configuration is less distorted than the ones from the iXBlue 4μm v2 at comparable gain G_0, which confirms that the iXBlue 5μm has a larger saturating energy than the iXBlue 4μm v2. The distortion effect is the result of the gain depletion in the amplifier. Using the Frantz-Nodvik model this can be predicted. The Frantz-Nodvik model applied on the output pulses of the pre-amplifier and the booster stage gave us the dashed curves for the three different gain level studied. We note a strong difference between the measured pulse shape and the shape modeled by the Frantz-Nodvik equation for both single clad TDF configurations and different gain level.

One way to prevent this gain depletion is to use a pre-shaped pulse coming out of the semiconductor laser diode. This has been demonstrated for 100 ns pulses in TDFL based on direct modulation in the paper by H. Shi et al. [2].

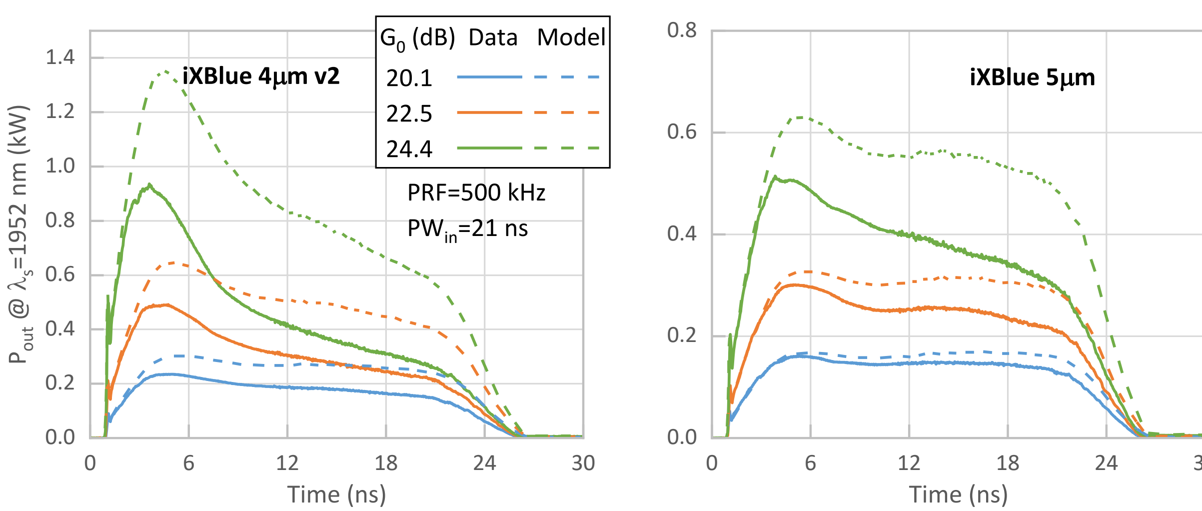

Figure 8: Output pulse shape for for the iXBlue 4um_v2 (left) and the iXBlue 5um (right).

The output pulse width (PW_{out}) evolution versus pump power was measured for different input pulse widths and is shown in Figure 9 for the two TDF single clad configurations. We observed that for the iXBlue 4μm v2 configuration, the output pulse width depends on the pump power and the input pulse width: at low pump power the pulse width is independent of the pump power whereas above 6 W of pump power we observe a decrease of the pulse width with an increasing pump power. The pulse width seems to converge towards a value of 5-6 ns. With the iXBlue 5µm configuration, we did not observe a dependence of the output pulse width on the pump power. This confirms the effect difference in gain depletion observed in Figure 8 for the the iXBlue 4µm v2, which has a lower saturation energy than the iXBlue 5µm.

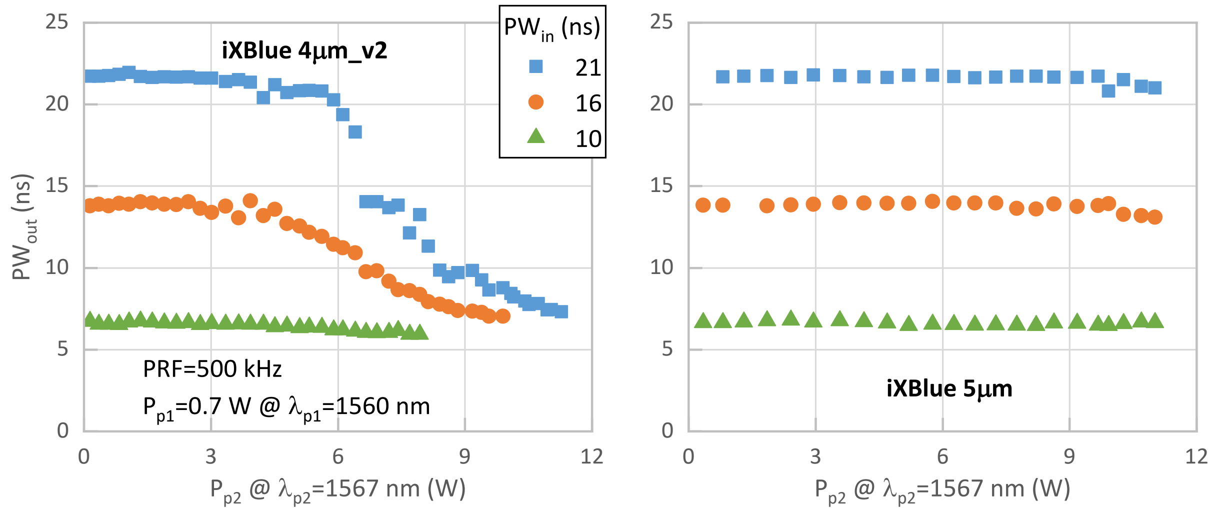

Figure 9: Output pulse width versus output energy for three different input pulse widths for the iXBlue 4um_v2 (left) and the iXBlue 5um (right).

Next, we studied the dependence of the performance on the input pulse width. Figure 10 shows the evolution of the pulse peak power with the pump power for three different input pulse widths for both single clad configurations. We observed for both configurations that with a decreasing pulse width, the peak power increases non-linearly. For the iXBlue 5µm configuration, at a pump power of 5.8 W the output peak power is 1.4 kW, 1.8 kW, and 2.5 kW for a pulse width of 21 ns, 14 ns, and 6 ns, respectively.

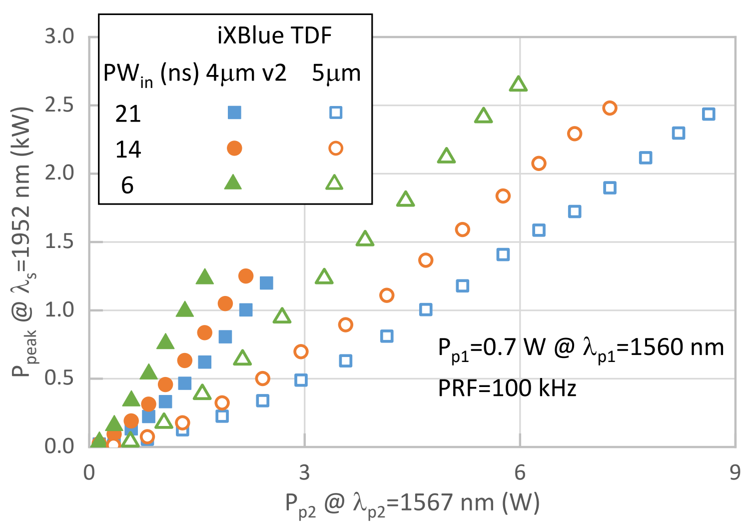

Figure 10: Peak power versus 1567 nm pump power for three different input pulse width.

The normalized output spectrum of the iXBlue 5µm configuration is shown for an output peak power of 2.5 kW for different input pulse width in Figure 11. We observed no significant difference in the output spectra with the different input pulse width. The side lobes on each side of the signal are attributed to the modulation instability (MI) due to the high peak power combined with the chirp of the semiconductor seed laser. At a wavelength of 1952 nm the dispersion of the Thulium-doped fiber was measured to be -18 $ps^2.nm^{-1}$ [6] which is one of the requirements to have MI. The MI results from four-wave mixing between the signal and the noise, and limits the power amplification as the energy is transferred to the side lobes.

At an output peak power of 2.5 kW, less than 1 % of the energy is in the side lobes. The setup had an output pigtail of 1 m long (Nufern SM1950) to limit the generation of non-linearities. Therefore one way to reduce the MI is to shorten the output pigtail length (e.g. 0.5 m or less).

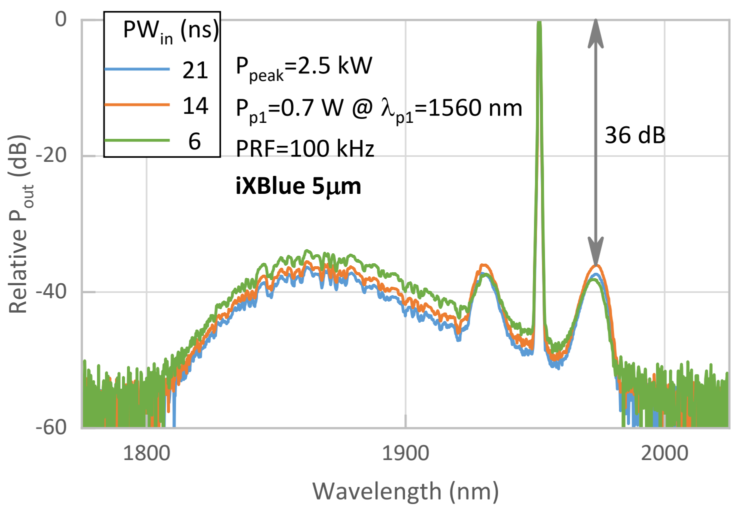

Figure 11: Output spectrum for different 1567 nm pump power.

5. CONCLUSION

We demonstrated two TDFL topologies based on direct modulation of a semiconductor laser diode, operating at 1952 nm, which can deliver more than 1 kW of peak power for three different pulse width (i.e. 6, 14, and 21 ns) and a wide range of pulse repetition frequencies (i.e. 10 to 500 kHz). Our setup was composed of a pre-amplifier followed by a booster stage. The pre-amplifier was designed to deliver high gain to saturate and extract the energy from the booster stage. It delivered output peak powers between 5 and 9 W for pulse repetition frequencies between 2 MHz and 10 kHz, respectively. In the booster stage we investigated two single clad TDFs from iXBlue with different saturating energies. Using the iXBlue 4μm v2 the TDFL delivered up to 12 μJ while with iXBlue 5μm yielded up to 29 μJ. Through gain depletion of the active fiber, we observed a distortion of the pulse shape, which reduces the output pulse width, for PRF less than 2 MHz for the iXBlue 4μm v2 and less than 500 kHz for the iXBlue 5μm. The maximum output peak powers reached are 1.2 kW and 2.5 kW for the iXBlue 4μm v2 and iXBlue 5μm, respectively.

6. ACKNOWLEDGEMENTS

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7. BIBLIOGRAPHY

[1] H. Shi, J. Liu, K. Liu, F. Tan, P. Wang, 160 W average power single-polarization, nanosecond pulses generation from diode-seeded thulium-doped all fiber MOPA system, in: SPIE Fiber Lasers XII Technol. Syst. Appl., 2015: p. 93441O. doi:10.1117/12.2079343.

[2] H. Shi, F. Tan, Y. Cao, P. Wang, P. Wang, High-power diode-seeded thulium-doped fiber MOPA incorporating active pulse shaping, Appl. Phys. B. 122 (2016) 269. doi:10.1007/s00340-016-6543-4.

[3] C. Romano, R.E. Tench, J.-M. Delavaux, 5W 1950nm Brillouin-free efficient single clad TDFA, in: Laser Technol. Def. Secur. XIV, 2018. doi:10.1117/12.2304910.

[4] C. Romano, R. Tench, J. Delavaux, 8W 1952nm Highly Efficient Brillouin-free Single Clad TDFA, in: ECOC Pap. We2.5, 2018.

[5] C. Romano, R.E. Tench, J.-M. Delavaux, Y. Jaouen, Characterization of the 3F4–3H6 Transition in Thulium-Doped Silica Fibres and Simulation of a 2µm Single Clad Amplifier, in: 2017 Eur. Conf. Opt. Commun., IEEE, Gothenburg, 2017: pp. 1–3. doi:10.1109/ECOC.2017.8345894.
[6] S. Kharitonov, A. Billat, C.-S. Brès, Kerr nonlinearity and dispersion characterization of core-pumped thulium-doped fiber at 2 µm, Opt. Lett. 41 (2016) 3173. doi:10.1364/OL.41.003173.