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Abstract:

A distributed feedback (DFB) diode, gain switched to produce pulses from 60 ps at high peak power of over 0.5 W, is used in burst mode to seed a fiber amplifier chain. High seed power, spectral filtering between amplifier stages and pulsed pumping are used to mitigate amplified spontaneous emission (ASE). The effect of pulse pumping synchronised with the seed on the ASE is explored for the power amplifier at low repetition. Different input and output energies at different burst repetition rates are examined and up to 85 % reduction in ASE is achieved compared to continuous pumping. Finally, a numerical model is used to predict further reduction of ASE.

Keywords: Fiber laser; Ytterbium doped; Laser amplifiers.

1. Introduction

Using bursts of pulses instead of single pulse has shown to be beneficial in certain micromachining [1-3], medical [4, 5] and scientific [6, 7] applications. Using this technique in fiber lasers allows simple burst energy scaling to achieve high average powers at short pulse durations [8] while avoiding the onset of nonlinear effects since the peak power of individual pulses within the burst can be kept at a lower level. This is especially important when amplifying ultra-short pulses where the nonlinearities limit the achievable pulse energies [9, 10]. Typically, a burst consist of several pulses, depending on the application up to 20 or more, at high repetition rate (MHz range) and is repeated with the burst repetition rate usually variable in the kHz range to adapt to the machining process. A problem with amplifying bursts in fiber amplifiers is the gain saturation, which distorts the shape of the amplified bursts. Since the first demonstration of a burst-mode fiber laser [11], different techniques to overcome this issue were presented. Breitenkopf et al. [12] used a sufficiently high pumping power (1.6 kW) in order to rebuild the population inversion between individual pulses within a burst. Another method is to preshape the burst before it enters the amplifier, either with an adaptive feedback loop [13], or by using a theoretic model that can effectively compensate for the gain saturation [14, 15]. The latter can be extended to multi-amplifier setups, as we have shown in [16].

To produce the appropriate pulse shape at desired repetition rate gain switched laser diodes are used, usually with the distributed feedback architecture for producing pulses as short as several tens of picoseconds. The peak power at this short scale is around several 100 mW as reported in [17] where a 300 mW 50 ps pulses were achieved. Increasing the pulse length to nanosecond scale results in higher peak power [18]. Higher power from the seeder allows for a less complicated preamplifying stage and less amplified spontaneous emission (ASE) before the burst-shaping element. A fiber-amplifier chain seeded in such a way can operate at various repetition rates depending on the application.

At very low burst repetition rates (e.g. <10 kHz), ASE limits the achievable burst energy and can even lead to thermal damage of the fiber components at the input of the amplifier due to its propagation in the opposite direction. In order to reduce the amount of ASE in a burst-mode fiber amplifier pulsed pumping of the active fiber can be employed [19]. Using this technique the active fiber is pumped with short pulses just before

the laser burst enters the fiber. Consequently, the population inversion is kept at a lower level for most of the time resulting in lower average ASE power.

In this paper we present a theoretical and experimental study of the effect the pulsed pumping has on the amount of ASE in a burst-mode fiber amplifier operating at 1064 nm and seeded by a DFB diode with a custom driving unit allowing for short picosecond pulses at increased peak power.

2. Experimental setup

A distributed feedback (DFB) laser diode producing pulses with a tuneable duration from 60 ps to more than 1 ns at 40 MHz repetition rate and emitting at 1064 nm wavelength was used as a seed for a four-stage polarization maintaining (PM) fiber amplifier.

We developed a special driver allowing higher peak power of the seed diode at pulse duration of only several tens of picoseconds. The driver was fine-tuned to avoid producing any secondary oscillations of the output power while enabling fast gain switching on the picosecond scale as shown in Fig. 1 for a 60 ps pulse. Additionally, the diode could be used up to the nanosecond range producing pulses with high peak power. The driver also enabled synchronization of the burst shaping acousto-optic modulator (AOM) and the pulsed pumping of the last amplifying stage.

Fig. 1. The output power of the optical pulses produced by the distributed feedback (DFB) seed diode. The shortest (60 ps) pulse (blue line) virtually does not exhibit any unwanted secondary fluctuations in power.

The experimental setup of the four-stage amplifier system is based on the setup previously reported in [16] and is shown in Fig. 2. Bursts of pulses were cut out and preshaped from the 40 MHz pulse train of the DFB seed diode using an AOM. The input burst shapes were determined using our closed-form theoretical model of gain saturation presented in [16] in order to obtain a flat output burst, i.e. equal pulse energy of each pulse within the burst. The bursts consisted of an arbitrary number of pulses at arbitrary burst repetition rates. However, to characterize ASE influence at low repetition rates, this paper presents only bursts containing 20 pulses separated in time by 25 ns at burst repetition rates from 1 kHz to 20 kHz. This upper limit was chosen because ASE does not usually limit the achievable burst energy at higher repetition rates and no significant improvement is expected by employing pulsed pumping. A typical preshaped input burst and the corresponding output burst are shown in Fig. 3.

All amplifier stages were isolated from each other using optical isolators and band-pass filters in order to remove all ASE that would otherwise be further amplified in consecutive amplifier stages. The 25 W pump diode of the last amplifier stage was synchronized with the seed diode and with the AOM using an adjustable delay which was set in a way that the burst arrived precisely at the end of the pump pulse, as shown schematically in Fig. 2.

All three preamplifiers were pumped continuously with the pump power adjusted in such a way that the input burst energy at the last amplifier was fixed 0.75, 1.5 and 3 μ J, at arbitrary burst repetition rate. Furthermore, the pump pulse duration of the last amplifier was adjusted in such a way that the output burst energies of 75, 150 and 300 μ J were

achieved and the amount of ASE was measured at each setting. The power of ASE was measured using a short-pass filter with a cut-off wavelength at 1050 nm. Finally, the measurements were compared to continuous pumping of the last stage (in this case the pump power was adjusted instead in order to achieve the target burst energies).

Fig. 2. Experimental setup consisting of a gain-switched laser diode producing pulses at 40 MHz repetition rate and a four-stage fiber amplifier. All active fibers in all amplifiers are Yb-doped with core absorption of 1200 dB/m at 976 nm pump wavelength. The fiber lengths of each consecutive amplifier stage are 90 cm, 60 cm, 50 cm and 180 cm, respectively and all amplifiers are pumped with 976 nm laser diodes. The pump diode of the last amplifier stage is synchronized with the seed and with the acousto-optic modulator (AOM). The AOM is used to preshape bursts from the input pulse train. An additional band-pass filter is used at the output of the third amplifier stage in order to remove all ASE from the input of the last amplifier stage. At the output of the final amplifier a dichroic mirror is used to remove the residual (unabsorbed) pump light (not shown).

Fig. 3. (a) Typical input burst shape (after the acousto-optic modulator) consisting of 20 pulses at 40 MHz repetition rate. (b) Amplified burst (150 μJ) at the output of the final amplifier. Red circles show the averaged (over 100 bursts) peak power of each pulse within the burst.

3. Results and discussion

The power of ASE before the power amplifier was reduced to negligible level by the employment of the DFB diode with high peak power and spectral filtering. The influence of pulsed pumping of the last amplifier is now further investigated and the results are compared to continuous pumping. Measured average ASE power at various input and output burst energies as a function of burst repetition rate is shown in Fig. 4. The pulsed pumping is especially beneficial at low burst repetition rates and for high amplification levels (e.g. amplifying 1.5 μJ bursts to 300 μJ , i.e. 200x amplification). At 1 kHz repetition rate and 50x amplification, using pulsed pumping, the amount of ASE was reduced by ~50 % when compared to continuous pumping. At higher amplification levels (100x and 200x), ASE was reduced by ~70 % and ~85 % respectively. Increasing the repetition rate results in smaller reduction in ASE because of the higher pump duty cycle, defined as the ratio between pump pulse duration and the time between two bursts. With high duty cycle, the operating conditions are becoming comparable to continuous (CW) operation, which corresponds to only ~20 % decrease of ASE power for 20 kHz repetition rate. In Fig. 5, the fraction of ASE in the total output power is shown and is calculated as:

$$\text{ASE Fraction} = \frac{\text{ASE}}{\text{ASE} + \text{Signal}} \quad (1)$$

and is expressed in percent of the total output power. As before, the effect of pulsed pumping is more significant at lower repetition rates and higher amplification levels. Using pulsed pumping the fraction of ASE was kept below ~10 % for all combinations of the input and output burst energies, whereas using continuous pumping, the fraction of ASE exceeded 40% at the highest amplification level for low repetition rates. Additionally it can be seen that with pulsed pumping at low repetition rates, ASE fraction is not decreasing monotonically with the increasing amplification ratio (Fig. 5; e.g. asterisk for 1 kHz). This is due to gain depletion between the individual pulses in the burst, which is also the time when the spontaneous emission is amplified. Low amplification means a shallower transient in population inversion of the amplifier and more gain for ASE whereas at higher amplification, the transient is deeper and the ASE gain is smaller. The same reasoning lies behind the different slopes of the ASE fraction versus repetition rate plots shown in Fig. 5 for pulsed pumping.

Fig. 4. Amplified spontaneous emission (ASE) powers at various input and output burst energies as a function of burst repetition rate for pulsed pumping (PLS) and continuous pumping (CW). A significant reduction in ASE is observed at low burst repetition rates.

Fig. 5. Fraction of amplified spontaneous emission (ASE) power in the total output power at various amplifications as a function of burst repetition rate for pulsed pumping (PLS) and continuous pumping (CW).

The pump pulse durations required to achieve the target burst energies as well as the pump duty cycle are shown in Fig. 6. Longer pump pulses are required at lower repetition rates since the population inversion is depleted more between individual bursts. Because of this, the ASE is suppressed more significantly at lower burst repetition rates. The pump duty cycle on the other hand increases with increasing repetition rate, i.e. the pumping conditions are more and more similar to continuous pumping at higher repetition rates. This correlates to the less significant effect of pulsed pumping at higher repetition rates shown in Fig. 4 and Fig. 5. Using a pump source capable of higher pump pulse powers would decrease the pumping time and the duty cycle, consequently further improving the signal to ASE ratio.

Fig. 6. (a) Pump pulse durations as a function of burst repetition rate, for different input and output burst energies. (b) Pump duty cycle as a function of burst repetition rate, same input and output burst energies as in (a).

In order to get a more general picture and to predict the effect of higher pump powers a numerical model based on [20] was used to determine the ASE power under such conditions. The numerical model solves the appropriate partial-differential rate equations numerically, by integrating the rate equations along the fiber length with small temporal increments. The integration is performed in both directions (forward and backward) alternately until the results converge to a stable solution for signal, pump and ASE powers in both directions. The measured input burst energy and pump power were used as input data for the model. Other parameters were obtained from the manufacturers' specification

for Liekki Yb1200 25/250 fiber (e.g. pump cladding absorption, fiber geometry etc.) and were varied within the specified tolerances in order to obtain the best fit with our experimental data.

The results of the model for a specific case of amplifying 1.5 μJ bursts to 150 μJ are shown in Fig. 7. As expected, using a more powerful pump source is mostly beneficial at higher repetition rates. At 20 kHz a further ~25 % reduction of ASE can be expected by doubling the pump power (to 50 W) and even ~40 % reduction of ASE by quadrupling it (to 100 W).

Fig. 7. Results of the numerical model for a specific case of amplifying a 1.5 μJ burst to 150 μJ , using 25 W pump power (red line, compared to the experimental data shown with red asterisks), 50 W pump power (blue line) and 100 W pump power (purple line). The power of ASE (left) and the necessary pump pulse duration (right).

It should be noted however that the higher pump powers, while reducing the average ASE power, do not necessarily lead to less ASE within the duration of the burst. In fact, our model predicts no significant change in the power of ASE within the burst while using more powerful pumping. This is because the population inversion at the exact time the burst enters the active fiber should be the same, regardless of the pumping power (in order to achieve the same target burst energy). In other words, higher pump power reduces the time required to increase the population inversion to a sufficient level consequently reducing the accumulated ASE energy before the burst arrives, while the peak power of ASE is mainly unaffected. This ASE power then decays during the burst and accumulates to a similar ASE energy within the burst regardless of the pump power used to pre-pump the fiber.

This implies that if another AOM is used at the output of the amplifier as a fast shutter/pulse-picker, the amount of ASE will not be reduced significantly by using a more powerful pump source. This should be taken into account when optimizing the laser for certain applications that are sensitive to ASE background where sacrificing the low-cost as well as efficiency in terms of the high pump power required to achieve a relatively low output power, might not produce a significant improvement of the laser-processing results.

4. Conclusion

In this paper a DFB laser diode was used, driven with a custom-made electronics to produce pulses of several tens of picoseconds with peak powers of over 0.5 W. The driver and the controller systems were used together in a burst mode fiber amplifier to study the ASE reduction when operating at lower repetition rates. Strongly driven DFB seed diode, spectral filtering of ASE from preamplifiers and pulsed pumping were used to reduce ASE. We have shown that by using pulsed pumping ASE can be significantly reduced in a burst-mode fiber amplifier operating at 1064 nm. Up to 85 % reduction in ASE power was achieved at 300 μJ burst energy and 1 kHz burst repetition rate. The fraction of ASE within the total output power was kept below ~10 % at all the evaluated input and output burst energies. Using our numerical model further improvement at higher repetition rates is predicted in case of a more powerful pump source.

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