Pre-print of a published manuscript

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Published in:

Applied optics, Volume 54, May 2015, Pages 4629-4634

Received: 6 March 2015

Accepted: 21 April 2015

Available online: 11 May 2015.

DOI: <https://doi.org/10.1364/AO.54.004629>

This is the pre-print of the article. For citing please follow to the link for the final authenticated version of the article: <https://doi.org/10.1364/AO.54.004629>

Research funding:

ARRS - Slovenian Research Agency (P2-0270, P2-0392) Projects L2-6780.

The article relates to SPS Operation entitled Building blocks, tools and systems for future factories – GOSTOP.

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

A low-power source, such as a gain-switched laser diode usually requires several amplification stages to reach sufficient power levels. When operating in burst mode, a correct input burst shape must be determined in order to compensate for gain saturation of all amplifier stages. In this paper we report on closed-form equations that enable saturation compensation in multi-amplifier setups, which eliminates the need for an adaptive feedback loop. The theoretical model is then evaluated in an experimental setup.

OCIS codes: (140.3510) Lasers, fiber; (140.3615) Lasers, ytterbium; (140.3280) Laser amplifiers; (140.3430) Laser theory.

<https://doi.org/10.1364/AO.54.004629>

1. Introduction

Pulsed fiber lasers and amplifiers are becoming widely used in many application areas. Different techniques are used for producing pulses from fs to ns range. In the ns range direct diode modulation and Q-switching is the most common method. The latter usually employs an acousto-optic modulator [1], a saturable absorber [2, 3] or other alternative techniques such as cavity dumping [4] and photo-elastic modulators [5]. The most compact fiber laser design to achieve ns pulses is based on laser resonator gain-switching [6-11], however it is rarely used as it cannot offer high peak powers. For ultra-short pulses (<10 ps) a master-oscillator power-amplifier (MOPA) scheme is usually used, where the laser source is a mode-locked laser and chirped-pulse amplification (CPA) is used to avoid nonlinear effects in fibers [12-17]. Such lasers provide the shortest pulses with highest pulse peak powers at the expense of increased complexity and cost. Another possibility is pre-chirping the pulses to achieve the shortest pulse duration directly from the laser, without the need for an additional compressor [18]. In certain applications, pulses in the range of tens of ps can provide performance similar to ultra-fast pulses, while enabling the use of less-complex laser sources. Such laser pulses can be obtained using gain-switching. Usually when gain switching of a fiber laser is applied a compact and high efficient laser can be obtained [6, 9, 10]. However in NIR range the shortest pulse duration recently reported [7] far exceed sub ns range. The pulse duration of the gain switched laser is related to the resonator length [7], which in the case of the fiber laser is in the range of 1 m, and also the pumping rate. In order to get pulses with much shorter duration a laser source with much shorter resonator length needs to be used. Laser diodes seem to be the perfect solution [19, 20], however in order to achieve a reasonable average and peak power, a special type of ultra-high speed (rise/fall time in range of

100 ps) and high voltage (> 20 V) drivers have to be used. By using a gain-switched laser diode and an adequate amplifier chain, an efficient laser system with pulse duration from ~20 ps to ~1 ns can be built. A fiber amplifier is almost a perfect tool for amplifying weak signals of a gain-switched laser diode. However, the main challenge of directly amplifying ps pulses in order to achieve sufficient pulse energy, required by typical industrial applications, such as laser micromachining, is the onset of nonlinear effects. A possible solution is the burst mode operation [21, 22], where several pulses at high repetition rate are stacked into bursts of pulses, which have a lower repetition rate. This allows for scaling of the total burst energy, without exceeding the nonlinear thresholds of individual pulses. Also, using bursts instead of single pulses can be beneficial in certain micromachining applications [23-25]. However, one of the key problems with burst amplification is the saturation of the active medium, which is an intrinsic property of any optical amplifier. If the burst energy becomes large enough, population inversion decreases within the duration of the burst and consequently the first part of the burst is amplified more than the last part of the burst, resulting in a change of burst shape at the output of an amplifier. To achieve the usually preferred square shape of the output bursts it is therefore necessary to correctly modulate the input bursts such that the saturation effect is canceled-out by the modulation function. This can be done either with applying an adaptive feed-back loop mechanism which continually measures the output burst shape and modifies the input burst shape so that the desired output burst shape is achieved [26, 27]. Another approach is using a theoretical model of gain saturation dynamics. Such model using a set of closed-form equations for a single amplifier, seeded by a single pulse was already reported [28]. When amplifying a low-power laser source such as a gain-switched laser diode however, several amplifier stages are usually required, therefore every amplifier stage that contributes to saturation effect needs to be

considered. Here we report on closed-form equations that can be used to generate a correct modulation function in a multi-stage amplifier, and only require the input and output powers of each amplifier stage to be known, meaning that the modulation function can be generated in real-time for any pump powers of the amplifiers without using a relatively complex adaptive feedback loop.

2. Theory

The model of burst saturation is based on Frantz-Nodvik pulse amplification equations [29], where the pulse shape at the output of an amplifier is given by:

$$P_{out}(t) = \frac{P_{in}(t)}{1 - C \exp\left(-\frac{1}{E_s} \int_0^t P_{in}(\tau) d\tau\right)}, \quad (1)$$

where P_{in} and P_{out} are input and output powers respectively and C is calculated from the initial population inversion and determines the unsaturated amplification of the amplifier. The saturation energy of a fiber amplifier is:

$$E_s = \frac{\hbar \omega A_{eff}}{2\sigma_s}, \quad (2)$$

where A_{eff} is the effective mode field area and σ_s is the stimulated-emission cross-section. The Frantz-Nodvik equations are based on a simple two-level system, i.e. there is no relaxation of the lower energy level of the amplifying medium. Consequently, every emitted photon reduces the population inversion by 2. It can be shown that Eq. (1) is still valid for the case of pulses with duration significantly larger than the lifetime of the lower energy level ($\tau \sim 1$ ns for Yb active medium). This is the case where every emitted photon reduces the population inversion by 1 i.e. the lower energy level is empty throughout the duration of the pulse. However the saturation energy is then:

$$E_s = \frac{\hbar \omega A_{eff}}{\sigma_s} \quad (3)$$

For pulses with duration around τ , the saturation equations can only be solved numerically (i.e. Eq. (1) and the following closed-form equations are not valid). The durations of bursts reported in this paper are from 250 ns to 1 μ s, therefore the saturation energy from Eq. (3) is used. Another required assumption is that pumping of the amplifier can be neglected during the duration of a burst. This means that the burst duration must be small in comparison to burst repetition period. We also note that results are equivalent for bursts of pulses, as well as for single pulses, as long as the former assumptions are valid. For simplicity, the following calculation is based on the fact, that a homogeneous burst can be replaced with a square pulse having the same duration T_b and the same energy E_b as the entire burst. The power $P(t)$ of such square pulse is then:

$$P(t) = \frac{E_b}{T_b}, \quad \text{for } 0 \leq t \leq T_b. \quad (4)$$

In order to produce homogeneous-square bursts at the output of the amplifier (i.e. peak powers of individual pulses in bursts are equal) one must employ input burst modulation. The correct input burst shape can be determined by inverting the Frantz-Nodvik equations to get the shape of the input burst in order to produce a square burst at the output with power:

$$P_{out}(t) = \frac{E_{out}}{T_b}, \quad (5)$$

where E_{out} is the output burst energy and the burst is again, for simplicity, replaced with a square pulse. The required input burst shape can be calculated by rearranging Eq. (1) as follows:

$$\int_0^t P_{in}(\tau) d\tau = -E_s \left[\ln\left(1 - \frac{P_{in}}{P_{out}}\right) - \ln(C) \right]. \quad (6)$$

Derivative of the above equation (noting that C is a constant in time-domain) returns the following differential equation:

$$\frac{dP_{in}}{dt} = P_{in} \left(\frac{P_{out} - P_{in}}{E_s} + \frac{1}{P_{out}} \frac{dP_{out}}{dt} \right), \quad (7)$$

with the following general solution for a square output burst:

$$P_{in}(t) = \frac{E_{out}}{T_b} \frac{1}{1 + K \exp\left(-\frac{E_{out}t}{E_s T_b}\right)}, \quad (8)$$

where K is a constant. By integrating the above equation over t we get the input burst energy E_{in} from which we determine K :

$$\int_0^{T_b} P_{in}(t) dt = E_{in} = \frac{E_{out}}{T_b} \int_0^{T_b} \frac{dt}{1 + K \exp\left(-\frac{E_{out}t}{E_s T_b}\right)}, \quad (9)$$

$$K = \frac{\exp(E_{out}/E_s) - \exp(E_{in}/E_s)}{\exp(E_{in}/E_s) - 1}. \quad (10)$$

This is the optimum burst-shape to obtain a square output burst from a single amplifier and is equivalent to the result given in [28].

By continually monitoring the input and output burst energies (i.e. average powers at input and output of the amplifier) it is therefore possible to adjust the input burst shape in real-time for arbitrary amplifier pump powers. Using the same steps as above it is generally possible to calculate the modulation function for any simple output burst shape. E.g. to achieve a saw-shaped output burst, i.e.:

$$P_{out}(t) = \frac{2E_{out}}{T_b^2} t, \quad \text{for } 0 \leq t \leq T_b, \quad (11)$$

the input burst should have the following shape:

$$P_{in}(t) = \frac{2E_{out}}{T_b^2} \frac{t}{1 + K \exp\left(-\frac{E_{out}t^2}{E_s T_b^2}\right)}, \quad (12)$$

where the constant K has the same value as in Eq. (10).

A typical master-oscillator power amplifier (MOPA) consists of several fiber-amplifier stages. In general, all amplifier stages that add to the effect of saturation should be considered, when determining the correct modulation function i.e. all amplifier stages, where burst energies reach the order of magnitude of the saturation energy of the particular stage. Since the core diameters used in the first amplifier stages are usually smaller this also leads to lower saturation energies of these stages as seen in Eq. (3). For N amplifier stages with input and output burst energies $E_{in,k}$ and $E_{out,k}$, saturation energies $E_{s,k}$, and coupling efficiencies $\eta_k \leq 1$ between amplifier $k-1$ and k , the required input burst shape at the first amplifier stage is found by recursively applying the same technique as above, i.e. using the result from Eq. (8) in Eq. (7) for every amplifier stage. By doing so we obtain the following recursive rule for the input burst shape at the k -th amplifier stage $P_{in,k}(t)$, which results in a square burst shape at the output of the final amplifier.

$$P_{in,N}(t) = \frac{E_{out,N}}{T_b} \frac{f_0(t)}{f_0(t) + K_N}, \quad (13)$$

$$P_{in,k}(t) = \frac{P_{in,k+1}}{\eta_{k+1}} \left(1 - \frac{K_k}{g_k(t)} \right),$$

where

$$f_0(t) = \exp\left(\frac{E_{out,N}t}{E_{s,N}T_b}\right). \quad (14)$$

To determine the constants K_k and functions $g_k(t)$ we first define

$$\gamma_k = \frac{E_{s,k}}{\eta_k E_{s,k-1}}. \quad (15)$$

Using this notation we can determine the constants K_k :

$$K_k = \frac{a_k - b_k \exp(E_{in,k}/E_{s,k})}{\exp(E_{in,k}/E_{s,k}) - 1}, \quad (16)$$

Where a_k and b_k follow the recursive rule:

$$\begin{aligned} a_N &= \exp(E_{out,N}/E_{s,N}) \\ b_N &= 1 \\ a_k &= (K_{k+1} + a_{k+1})^{\gamma_{k+1}} \\ b_k &= (K_{k+1} + b_{k+1})^{\gamma_{k+1}}. \end{aligned} \quad (17)$$

Functions $g_k(t)$ also follow a recursive rule:

$$\begin{aligned} g_N(t) &= K_N + f_0(t) \\ g_k(t) &= K_k + [g_{k+1}(t)]^{\gamma_{k+1}} \end{aligned} \quad (18)$$

Using the equations above it is possible to determine the correct input burst shape for an arbitrary number of amplifier stages. In our experimental setup, the last two stages contributed to the burst shape distortion due to the saturation. For two amplifier stages with saturation energies $E_{s,1}$ and $E_{s,2}$, the input burst shape is found using the above equations:

$$P_{in,1}(t) = \frac{f_0(t)}{f_0(t) + K_2 + K_1 [f_0(t) + K_2]^{(1-\gamma_2)}}, \quad (19)$$

where

$$f_0(t) = \exp\left(\frac{E_{out,2}t}{E_{s,2}T_b}\right), \quad (20)$$

and the constants are

$$K_2 = \frac{\exp(E_{out,2}/E_{s,2}) - \exp(E_{in,2}/E_{s,2})}{\exp(E_{in,2}/E_{s,2}) - 1}, \quad (21)$$

and

$$K_1 = \frac{\left[K_2 + \exp\left(\frac{E_{out,2}}{E_{s,2}}\right) \right]^{\gamma_2} - (K_2 + 1)^{\gamma_2} \exp\left(\frac{E_{in,1}}{E_{s,1}}\right)}{\exp\left(\frac{E_{in,1}}{E_{s,1}}\right) - 1}. \quad (22)$$

In the equations above, $E_{in,1}$ and $E_{in,2}$ are input burst energies at first and second stage respectively and $E_{out,2}$ is burst energy at the output of the last stage.

To illustrate the need for multi-amplifier shape compensation when amplifying a low-signal source, we take a look at an example of amplifying a low-signal output from a gain-switched diode by A_0 i.e.: 30 dB, 35 dB and 40 dB using either a single amplifier or a two-stage amplifier. Such high amplification in a single amplifier stage would produce a significant amount of amplified spontaneous emission (ASE), so the more typical approach is using two amplifier stages, however the required input burst shape that results in a square output burst in a two-stage amplifier differs significantly from that of a single amplifier. For this example we consider adding a pre-amplifier stage to the power-amplifier, with saturation energy $E_{s,1} = 0.05 E_{s,2}$. This is a realistic case when using a single-mode pre-amplifier in combination with a Large-Mode-Area (LMA) power-amplifier. We distribute the amplification of both stages such that both amplifier stages are equally saturated, i.e. the amplifications of the first stage is $A_1 = A_0 E_{s,1}/E_{s,2} = 0.05 A_0$ and the amplification of the second stage is $A_2 = A_0/A_1$, where $A_0 = A_1 A_2$ is the total amplification. The input burst energy used in the example is $E_{in} = 10^{-4} E_{s,2}$. The distortion of the output burst shapes when using either a single amplifier stage, or a two-stage amplifier to achieve the same total amplification are shown in Fig. 1. The required input burst shapes to achieve a square output bursts in both cases are shown in Fig. 2. The effect of saturation in a two-stage amplifier is much more severe than in the case of a single amplifier stage with the same total amplification. Therefore it is necessary to use the appropriate multi-amplifier model to determine the correct burst shape at the input of an amplifier chain.

Fig. 1. Comparison of the output burst shapes from a single amplifier (dashed) and a two-stage amplifier (solid) with an unmodulated (square) input burst shape, for different total amplifications (30 dB, 35 dB and 40 dB).

Fig. 2. Comparison of the input burst shape that results in a square output pulse for a single amplifier stage (dashed) and for a two-stage amplifier (solid), for different total amplifications (30 dB, 35 dB and 40 dB).

3. Experimental setup

The experimental setup consisted of a pulsed gain-switched seed diode and four PM-fiber-amplifier stages with an acousto-optic modulator (AOM) with a rise time of 10 ns placed after the first amplifier stage as seen in Fig. 3. The seed diode produced 65 ps pulses with repetition rate 40 MHz at 1064 nm wavelength. The fiber diameter of the first two amplifier stages were 4 μm and exhibited no saturation, since the burst energies were far below the saturation energy of the active fiber. The fiber diameter in third stage was 6 μm and saturation of the amplifier was already visible at the output of the amplifier. The fiber used in the last stage was a 25/250 μm double clad fiber, where most of the saturation took place. Nevertheless it turned out that the saturation of both (last and second to last) amplifier stages were needed to be taken into account when determining the correct modulation function. The power and pulse train was measured between every amplifier stage using 1/99 fiber couplers as well as at the output of the amplifier system. Pulse trains were measured using an ultra - high speed photodetector.

Fig. 3. Experimental setup consisting of a gain-switched seed diode and 4 amplifier stages with AOM placed after the first amplifier stage.

4. Results

Using the AOM, several different bursts were produced consisting of 10, 20 and 40 pulses at repetition rate of 100 kHz and 200 kHz for each pulse-count as seen in Fig. 4. All pulse trains were measured with unmodulated and modulated bursts and compared to the theoretic model above. Using only 10 pulses per burst at 100 kHz repetition rate however produced a significant amount of stimulated Raman scattering, since the peak powers were well above 150 kW at the output of the last amplifier stage. Consequently these bursts were excluded from the evaluation of the theoretic model.

Fig. 4. (a) Seed diode pulse train and different burst shapes (10, 20 and 40 pulses at 100 kHz and 200 kHz repetition rate) that produce a flat burst at the output of the amplifier. (b) Measured input burst consisting of 20 pulses at 100 kHz burst repetition rate. (c) Measured input burst consisting of 20 pulses at 200 kHz burst repetition rate.

The modulation function for each burst duration and repetition rate was calculated from Eq. (19), where the measured input and output energies were used. Saturation energies to produce the most homogeneous output burst were however somewhat lower than expected from Eq. (3) and are summed in Table 1. The lower saturation energies might be due to the fact that Ytterbium is a quasi-three-level system, meaning that the lower energy level is always partially populated due to the thermal excitation which consequently decreases the saturation energy. Also the assumption that the pumping can be neglected during the duration of the burst is not entirely accurate. The pumping during the burst decreases the rate of de-population of the upper energy level and consequently increases the saturation energy. As seen in Table 1, the saturation energies used in the theoretic model were highest for bursts consisting of 40 pulses at 200 kHz repetition rate.

Table 1. Saturation energies used in the calculated modulation function for different burst durations and repetitions rate as well as expected saturation energies from Eq. (3). E_{s1} and E_{s2} are the saturation energies of the last two amplifier stages, used to achieve a flat output burst shape.

	E_{s1} [μJ]	E_{s2} [μJ]
40 pulses @ 100 kHz	10.8	270
40 pulses @ 200 kHz	11.2	280
20 pulses @ 100 kHz	10.4	260
20 pulses @ 200 kHz	10.8	270
10 pulses @ 200 kHz	10.2	255
From theory- Eq. (3)	~ 12	~ 300

However, by only applying the slightly lower saturation energies to the theoretic model, the resulting output burst shapes were flat with pulse-to-pulse stability between individual pulses in burst on the order of 1-2% and burst-to-burst stability around 1%.

The output burst shape, consisting of 40 pulses at 100 kHz repetition rate for an unmodulated and modulated input burst is shown in Fig. 5 and Fig. 6 (a) respectively. The unmodulated burst was strongly saturated, since the total burst energy was 133 μJ , with peak powers ranging from 71 kW (first pulse) to 33 kW (last pulse). The modulated burst consisted of pulses with peak power 46 kW, with pulse-to-pulse stability around 1%.

Fig. 5. Output burst shape with an unmodulated input burst consisting of 40 pulses at 100 kHz repetition rate.

Fig. 7. Output burst shape with a saw-shaped input burst consisting of 40 pulses at 100 kHz repetition rate.

Fig. 6. Output burst shape consisting of (a) 40 pulses at 100 kHz repetition rate, (b) 20 pulses at 100 kHz repetition rate and (c) 10 pulses at 200 kHz repetition rate, using the calculated modulation function.

The output burst shape, consisting of 20 pulses at 100 kHz repetition rate for modulated input burst is shown in Fig. 6 (b). The unmodulated burst was again strongly saturated, since the total burst energy in this case was 130 μ J, with peak powers ranging from 126 kW (first pulse) to 63 kW (last pulse). The modulated burst consisted of pulses with peak power 91 kW, with pulse-to-pulse stability around 2%.

Finally, the output burst shape, consisting of 10 pulses at 200 kHz repetition rate for modulated input burst is shown in Fig. 6 (c). The unmodulated burst was only weakly saturated, since the total burst energy was much lower due to the higher burst repetition rate and amounted to 64 μ J, with peak powers ranging from 103 kW (first pulse) to 77 kW (last pulse). The modulated burst consisted of pulses with peak power 89 kW, with pulse-to-pulse stability around 1%. In all three cases the total energy remained the same after applying burst modulation.

By using our theoretical model we can also construct almost arbitrary shape of the burst. For example the saturation when amplifying a saw-shaped input burst, as well as the output burst shape, when using an appropriate burst modulation to achieve a saw-shaped burst at the output of the amplifier chain are shown in Fig. 7 and Fig. 8 respectively.

Fig. 8. Output burst shape consisting of 40 pulses at 100 kHz repetition rate using the calculated modulation function for saw-shaped output burst.

5. Conclusion

In this paper we have shown that the previously reported theoretical model for saturation compensation in a single fiber amplifier is insufficient for amplifying low-power laser sources, such as a gain-switched laser diode, where several amplifier stages are usually required. An extended theoretical model for use in a multi-stage fiber amplifier is presented. Using this model, square bursts at the output of a fiber amplifier chain were achieved with a picosecond gain-switched laser diode source, with pulse-to-pulse stability $< 2\%$ and burst-to-burst stability around 1%, for different burst durations and burst repetition rates.

Acknowledgements

Operation part financed by the European Union, European Social Fund and by the Slovenian research agency ARRS (project L2-6780).

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