Pulsed dual-stage fiber MOPA source operating at 1550 nm with arbitrarily shaped output pulses

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Abstract In this paper we present an effective method of pulse distortion pre-compensation in saturated high-power fiber amplifiers by arbitrarily shaping the input pulse. We derive a simple expression which allows us to generate user-defined pulse shapes at the output of the amplifier chain consisting of more than one stage. The numerical results were verified experimentally using a diode-seeded all-fiber two-stage master oscillator–power amplifier (MOPA) source based on $\text{Er}^{3+}/\text{Yb}^{3+}$ -doped double-clad fiber. Several examples of obtained output shapes are presented, including high-energy 100-ns-long rectangular pulses.

1 Introduction

High-power pulsed fiber sources in MOPA (master oscillator–power amplifier) configuration have become a very attractive alternative to solid-state lasers in many technological and industrial applications. The mainstream of those constructions is currently dominated by diode-seeded ytterbium-doped fiber based systems operating in the 1- μm wavelength range [1–3]. They can provide high peak powers with freely adjustable kHz-level repetition rates and nanosecond pulse durations, which makes them useful in various applications like material cutting, drilling, engraving, etc. However, there are applications where Yb-doped sources cannot be used because of required eye safety, like

free-space communications, sensing, range finding or interferometry. In such areas high-power 1.5- μm wavelength sources are necessary. There are two main approaches to achieve 1550-nm radiation with good beam quality. One can use a diode-pumped microchip laser, but the maximum output power in such constructions is strongly limited to hundreds of milliwatts by the glass damage threshold [4]. The second approach is to build a laser based on rare-earth-doped fibers. Erbium/ytterbium co-doped fibers make excellent active gain media to build medium/high-power sources in the 1.5–1.6 μm region. Constructions using Er/Yb-doped fibers providing single-frequency multiple-watt continuous-wave (CW) output were already shown in the literature [5–7]. In the pulsed regime, the extractable energy is strongly limited by nonlinear effects (especially stimulated Brillouin scattering, SBS) and unwanted amplified spontaneous emission (ASE) which lead to fast self-saturation [8]. To increase the SBS threshold and maximize the possible pulse energy, several methods were presented. The most effective way to overcome the limitations is the usage of large mode area (LMA) fibers with >30- μm core sizes which allows us to achieve MW-level peak power with mJ pulse energy [9]. The consequence of using large-core fibers is a significant decrease of the beam quality due to multimode operation. Fabrication of single-mode LMA fibers can be problematic for the modified chemical vapor deposition (MCVD) method because Er/Yb fibers require high phosphorus doping to provide good pump absorption. This leads to critical difficulties in making low numerical aperture cores [10].

Extraction of high-power nanosecond pulses with kHz-range repetition rates in MOPA systems can lead to unwanted pulse-shaping effects. In such a system, when the amplifier energy reaches the saturation level the output pulse will be distorted. The leading edge of the pulse will get

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a high gain depleting the population inversion, so the rest of the pulse will be decreased exponentially [11, 12]. It is possible to compensate the disadvantageous influence of energy saturation by properly shaping the input pulse. These methods allow us to achieve arbitrarily shaped output pulses, meeting the requirements of some applications like nonlinear frequency conversion or material processing. For example, long, rectangular flat-top pulses are particularly desirable because of their highest possible energy. It has been already shown that different temporal pulse shapes used for material processing result in different surface qualities [13].

In our work we present a dual-stage MOPA source working in the eye-safe region (1550 nm) capable of generating user-defined output pulse shapes using an arbitrary function generator (AFG) controlled by a specially designed LabVIEW-based application to drive the seed laser diode. The temporal input pulse shapes are calculated using a simple model taking into account the pulse distortion in both amplifier stages. This allows us to obtain pulse shapes almost identical to the theoretical calculations, without using any additional pulse-shaping devices (like electro-optical modulators, according to Ref. [14]). Also, in contrast to

the methods which were presented recently [12, 14], we use the 1550-nm eye-safe working wavelength. In some particular applications with required eye safety, Er/Yb co-doped fiber sources outperform constructions based on Yb-doped fibers. Applying the pulse-shaping technique to those sources may increase their utility and effectiveness in various applications (range finding, sensing and material processing). Moreover, moving towards 1550 nm allows us to reduce the cost of the device, by using commonly available, relatively cheap telecommunication components (couplers, isolators, etc.).

2 Fiber amplifier design

Our all-in-fiber MOPA setup is shown in Fig. 1. It consists of two amplifying stages. The first stage (pre-amplifier) is an erbium doped fiber amplifier (EDFA) based on heavily erbium-doped fiber (Liekki Er80) pumped bidirectionally by two 700-mW, 980-nm single-mode pumps. It provides about 23-dB gain in the whole C-band with a very satisfactory noise figure (NF) of 4.5 dB. The second stage (power

Fig. 1 Two-stage MOPA design used in experiments

Fig. 2 Gain bandwidth of the MOPA system (a) and output spectra for different signals (b)

amplifier) is based on erbium/ytterbium-doped double-clad fiber with 7- μm core and 130- μm cladding diameter (Nufern EYDF-7/130). It is backward pumped by a 975-nm, 10-W laser diode (JDSU 6398L4i) coupled with the double-clad fiber by a pump combiner. The unabsorbed pump light from the second stage is rejected by a self-made cladding-mode stripper. Both stages are separated with an isolator which prevents the first stage from back-scattered light and allows us to avoid unwanted lasing in the amplifier. A standard telecommunication 1550-nm directly modulated distributed feedback (DFB) laser diode was used as a seed source. The driving pulses were generated from a Tektronix 1 GS/s arbitrary function generator (AFG) which provides samples with 1-ns resolution. The output shapes were observed using a digital 350-MHz oscilloscope coupled with a photodiode.

Obtained spectral characteristics of the whole MOPA system are shown in Fig. 2. As can be seen, it provides a flat gain in the 1540–1570 nm bandwidth. Spectral characteristics of four different output signals are shown in Fig. 2b.

The power characteristics of the two-stage amplifier operating in the CW mode are shown in Fig. 3. The graph shows also the corresponding unabsorbed pump power, measured by splicing another pump combiner (in reverse direction) instead of the mode stripper. The second combiner

allowed us to reject the 975-nm light through the multimode pumping ports.

The nonlinearity in the output power trace is caused by pump wavelength tuning due to temperature and current changes. The used 10-W laser diode is reaching its nominal 975-nm operation wavelength when the maximum current (11 A) is applied. The absorption peak of Yb^{3+} ions in the 975-nm region is very narrow, so even little changes in the pump wavelength can cause significant output power deviation. In our case the pump absorption was at the level of 97%.

3 Theory of pulse shaping in saturated fiber amplifiers

The pulse distortion effect in high-power diode-seeded fiber MOPA systems can be easily observed by giving a relatively long, rectangular pulse to the amplifier chain input. When the pulse energy reaches the saturation level, the output temporal shape will be deformed. The leading edge is getting a very high gain and there is no population inversion to amplify the rest of the pulse, so the amplitude will drop rapidly. Analytical expressions describing the distortion of a pulse traveling through the amplifier were already shown in the literature. They are mostly based on Frantz–Nodvik equations [15]. The output pulse shape is bound with the input through a gain function

$$I_{\text{output}} = I_{\text{input}} \cdot G(t), \quad (1)$$

where $G(t)$ is given by a simple exponential function [12]:

$$G(t) = 1 + (G_0 - 1) \cdot \exp\left(-\frac{E_{\text{out}}(t)}{E_{\text{sat}}}\right). \quad (2)$$

The parameters are: small-signal gain G_0 and saturation energy E_{sat} . They can be obtained experimentally by launching a rectangular pulse into the amplifier and approximating the output shape. The theoretical output shape for a 100-ns-long rectangular pulse can be seen in Fig. 4b.

Unfortunately, those equations do not take into account that the pulse is traveling through two amplifying

Fig. 3 Measured CW output power with unabsorbed pump power

Fig. 4 Rectangular input pulse (a) and the theoretical distorted output pulse (b)

Fig. 5 Rectangular pulse deformation in two-stage MOPA system (a) and measured output pulse (b)

Fig. 6 Experimental results—calculated input shapes and obtained output pulses

stages with their own $G(t)$ functions. In our case both the first and second stages are deforming the pulse exponentially, but with different time constants, as shown in the

scheme in Fig. 5a. Therefore, the $G(t)$ function of the whole two-stage amplifier will not be a simple exponential function, but a superposition of two exponential func-

Fig. 7 LabVIEW application to control the arbitrary function generator

tions: $G_1(t)G_2(t)$. The obtained response of the two-stage MOPA system to a rectangular input pulse can be seen in Fig. 5b.

If we assume a desired output pulse shape, we can rearrange (1) to calculate the required input I_{input} of a two-stage amplifier. It can be expressed as

$$I_{\text{input}} = \frac{I_{\text{output}}}{G_{\text{EDFA}}(t) \cdot G_{\text{EYDFA}}(t)}, \quad (3)$$

where G_{EDFA} and G_{EYDFA} are the gain functions of the first (EDFA) and second (EYDFA) amplifier stages, respectively. Such an input pulse shape pre-compensates the pulse distortion in the amplifier and allows us to get user-defined output pulse shapes. This equation can be simply expanded to be used in an N -stage amplifier chain. In this case, the complete $G(t)$ function should be a composition of N gain functions, corresponding to each amplifying stage.

4 Experimental results

Examples of obtained output pulses with corresponding input shapes are shown in Fig. 6. All of the pre-compensated input shapes are calculated from (3) using MATLAB, coupled with a LabVIEW-based application (Fig. 7) that controls the function generator. In all experiments the pulse duration is set to 100 ns, which is two times longer than reported previously in Ref. [12]. The repetition frequency was set to 100 kHz.

Basically, almost any output shape can be obtained using this method with a very good correlation between theoretical calculations and measurement results. The only observed

limitation is a strong peak at the beginning of pulses with rapidly rising edge, as in square pulses. It is caused by instabilities that occur when the laser diode is directly driven with pulses with very short rise times. In this case, the optical response of the diode is not identical to the electrical driving pulse—it has a strong peak at the beginning which is afterwards amplified in the chain and depletes the population inversion in the active medium. Traces shown in Fig. 8 illustrate this effect very well. Figure 8a shows the measured diode output when modulated with a short rise time (blue line) and with an optimized rise time (green line). The same rising edges are shown with higher resolution in Fig. 8b. A characteristic peak can be seen at the beginning of the pulse. This leads to some differences in the measured and calculated shapes. It can be clearly seen in Fig. 6a, d or e. This issue is relatively easy to overcome, just by extending the rise time, to make the leading edge smoother. An example of an optimized flat-top rectangular pulse is shown in Fig. 9. An almost ideal shape can be obtained just by linearly smoothing the leading edge of the input pulse.

The presented method of pulse distortion pre-compensation can be successfully applied to any other multistage fiber MOPA system. It can be extended to more (e.g. three or four) amplifying stages, just by adding subsequent sections to the equation. The only condition is to provide appropriate G_0 and E_{sat} parameters for each independent amplifier stage.

5 Conclusions

In conclusion, we have presented a simple and effective method of pulse distortion pre-compensation in high-power

Fig. 8 Measured diode output with different rise times: the whole pulse shape (a) and zoomed rising edge (b)

Fig. 9 Optimized input shape (a) and corresponding rectangular flat-top output pulse (b)

fiber amplifiers by properly shaping the seed diode driving pulses. Input pulse shapes were calculated using a numerical model, taking into account that the pulse is traveling through two amplifying stages with different distortion properties. The numerical results were verified experimentally by generating several pulse shapes using a two-stage fiber MOPA source. A very good correlation between the simulation and experiment can be observed.

Our method with linear smoothing of the leading edge allows us to avoid strong peaks at the beginning of the output shape. It is a much easier and cheaper way to obtain shapes, which are almost identical to the expected ones, than using iterative methods or setups with an electro-optical modulator as the pulse-shaping device.

The presented Er/Yb MOPA source with compensated pulse distortion can be considered as an effective light source for LIDAR systems, range finders or free-space telecommunication links.

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