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Arbitrary pulse shaping in Er-doped fiber amplifiers—Possibilities and limitations

Maria Michalska*, Jacek Swiderski, Marcin Mamajek

Institute of Optoelectronics, Military University of Technology 2 Kaliskiego Street, 00-908 Warsaw, Poland

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ABSTRACT

A temporal deformation of nanosecond laser pulses occurring during an amplification process in a two-stage erbium-doped fiber amplifier operating in saturation is presented. We discuss distortion of rectangular laser pulses with duration ranging from 5 ns to 300 ns, generated at 20 kHz repetition rate. Calculations of a suitable peak power scaling factor for distorted pulses are presented. A simple compensation method of temporal pulse distortion, based on the direct current modulation with the use of arbitrary function generator (AFG), is also reported. An appropriate input pulse shape modification leads to obtaining an output amplified pulse with any desired shape. The main limitation of pulse shaping in a fiber amplifier seeded by a narrow linewidth laser diode turns out to be stimulated Brillouin scattering (SBS). However, the pulse shaping method can also improve the amplifier performance by increasing the power threshold of SBS. SBS phenomenon in the context of arbitrary pulse shaping have been also discussed.

1. Introduction

Pulsed laser sources operating at the “eye-safe” ($\lambda > 1.4\ \mu m$) spectral range are desired for numerous applications like remote sensing, range finding, material processing, telecommunication, area mapping, and many others [1–3]. Most of these applications require optical pulses of short duration, usually on the nanosecond-scale and with kW level peak power. Pulses of such parameters can be easily obtained by *Q*-switching the optical cavity of both bulk and fiber lasers. However, in case of all *Q*-switched lasers the increase in repetition rate causes that the output pulse duration also increases (at constant pump power) and consequently, the pulse peak power decreases. This may be an obstacle for some applications, especially those where a high degree of pulse parameters control is needed. Therefore, the master oscillator power amplifier (MOPA) architecture which utilizes a low power pulsed seed laser followed by high-power amplification stages has been adopted. This technique is especially attractive if all system components, including a master oscillator and amplifiers, are developed in all-fiber technology, thus providing compactness, robustness, high environment insensitivity, and reliability.

Since the first demonstration of 1.55 μm amplification in an erbium-doped fiber [4] there has been an increasing interest in the development and optimization of these active devices. Spectroscopic properties of Er, and Er:Yb ions in commonly used silica hosts [5] or novel type of glasses [6,7] make them good candidates for gain media of eye-safe laser sources. The all-fiber pulsed MOPAs constitute one of the newest trends in optics and laser technology. Contrary to *Q*-switched lasers, in this approach a single mode semiconductor seed laser allows for a precise electric control of temporal (pulse width, pulse shape, repetition rate) and spectral parameters in a wide range [8,9]. The pulse train defined by the user is then amplified in a series of amplifiers to the energy/peak-power level required by a particular application. This unique flexibility makes high power MOPA systems very attractive for many industrial and technological applications.

Although low power and high power Er^{3+}-doped and Er^{3+}:Yb^{3+}-codoped fiber lasers and amplifiers operating in continuous mode (CW) have been successfully developed and many of them are commercially available, the construction of pulsed fiber-based laser sources, delivering short pulses at high repetition rates are still difficult. The main challenge concerns overcoming the undesirable nonlinear effects, like stimulated Brillouin (SBS) and Raman scattering (SRS), self phase modulation (SPM). Since in fiber lasers and amplifiers there is a relatively long interaction length combined with the high signal intensity, resulting from a small mode area of a propagating beam, the nonlinearities strongly affect an active system performance—by limiting their lasing or amplification possibilities. Besides, a very important issue is the saturation induced pulse shape deformation. Therefore, to achieve a high peak power output pulse of defined shape (e.g. rectangle)

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* Corresponding author. Tel.: +48 22 6837332; fax: +48 22 6668950.
E-mail address: mmichalska@wat.edu.pl (M. Michalska).

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a suitable modification of input pulse is necessary, to compensate temporal distortion. A few of pulse shaping methods incorporating the use of arbitrary function generator (AFG), direct current modulation and external optical signal modulation have been recently presented in the literature [10–14]. One can note that most of them [10–13] are related to Yb^{3+}-doped fiber amplifiers operating at $\sim 1\ \mu m$.

In this paper we report on 1.55 μm pulse amplification and deformation in a 2-stage EDFA, built in MOPA configuration. The pulse deformation process in a saturated fiber amplifier, a distortion compensation method, and the possibility of generation of pulses with different shapes are discussed theoretically and presented practically. SBS as a limiting factor of pulse amplification is also discussed. The experimental system delivers laser pulses with nanosecond (5–300 ns) duration and maximum—1.45 kW peak power at 20 kHz repetition rate.

2. Experimental setup

Theoretical analysis and experimental results on pulse amplification and distortion were carried out on an example of two-stage MOPA system, whose schematic view is shown in Fig. 1. A distributed feedback (DFB) laser (QDFBLD-1550-50, QPhotonics), pigtailed in a polarization maintaining (PM) single mode fiber was used as a seed of nanosecond pulses generated at the pulse repetition frequency (PRF) of 20 kHz. The DFB laser was supplied by a home built power supply with integrated pulse control system. An arbitrary function generator (Tektronix AFG 3252, 2.5 GS/s, 240 MHz bandwidth) providing the control of duration and shape of seed pulses, was also linked with the supply system. The repetition of generated pulse train could be independently changeable by a separate, home built current driver.

The pulse train form the DFB laser was amplified in a two stage EDFA. Both amplifying stages utilized heavily doped, single-mode, single-clad erbium-doped fibers (EDFs) with the core diameter of 8 μm and numerical aperture $NA = 0.2$ (Liekki Er80-8/125). Low power, single stage fiber optic isolators (>29 dB isolation), placed after the seed and between the amplifiers were used to block any undesirable back-coming radiation. Three wavelength-stabilized, fiber pigtailed laser diodes operating at 976 nm and each delivering of up to 600 mW were used to pump the active fibers. The single mode pump radiation was launched into the active fibers with the use of 980/1550 WDM couplers. A co-propagating, core pumping scheme incorporating a 1.2 m length of EDF was used in the first stage and a bi-directional pumping for 1.1 m EDF in the second stage. The maximum total gain, recorded for 5 ns pulses, was 46 dB, of which up to 33 dB was obtained in the first amplifier.

In order to eliminate out of band amplified spontaneous emission (ASE) a 200 GHz DWDM band-pass filter was fusion spliced between the amplifying stages. To monitor the pulse parameters a 2×2 (99%/1%) tap coupler was applied. It enabled the monitoring of pulses from the first amplifying cascade and backscattered SBS pulses. During measurements all temporal traces were recorded with the use of a sampling digital oscilloscope (Agilent, MSO7104B) with 1 GHz bandwidth and InGaAs photodetector with rise time of <100 ps. The output average power was measured by a power meter (Ophir, Laserstar) with thermal sensor.

3. Pulse shaping in a 2-stage Er doped fiber amplifier

3.1. Analysis of temporal pulse distortion in a saturated fiber amplifier

The distortion of a rectangular pulse in a saturated fiber amplifier has been already characterized and a thorough description can be found in Refs. [15,16]. When a rectangular pulse with energy comparable with the saturation energy E_{sat} of amplifying medium is launched into an amplifier, a significant pulse shape distortion can be observed. The saturation energy is defined by the following formula:

$$E_{sat} = \frac{h\nu_s A}{(\sigma_e + \sigma_a)\Gamma}, \quad (1)$$

where h is the Planck constant, ν_s—signal frequency, A—the active fiber core area, Γ—signal overlap with the active dopant, σ_e and σ_a—emission and absorption cross section at the signal wavelength. In our case E_{sat} was calculated to be about 13 μJ.

A pulse deformation is the consequence of population inversion change during an amplification process. The leading edge of the pulse depletes the most population inversion, thus experiencing higher gain than the trailing pulse edge. Furthermore, if a distorted pulse is launched into another, high power amplifier characterized by different gain function $G(t)$, a temporal distortion will be intensified and consequently, we obtain even several dozen shorter output pulse, whose shape has nothing in common with the initial rectangular pulse, but has very high peak power. This situation is depicted in Fig. 2.

The high pulse peak power in the system can limit the possible extractable energy form the active fiber. The pulse amplification

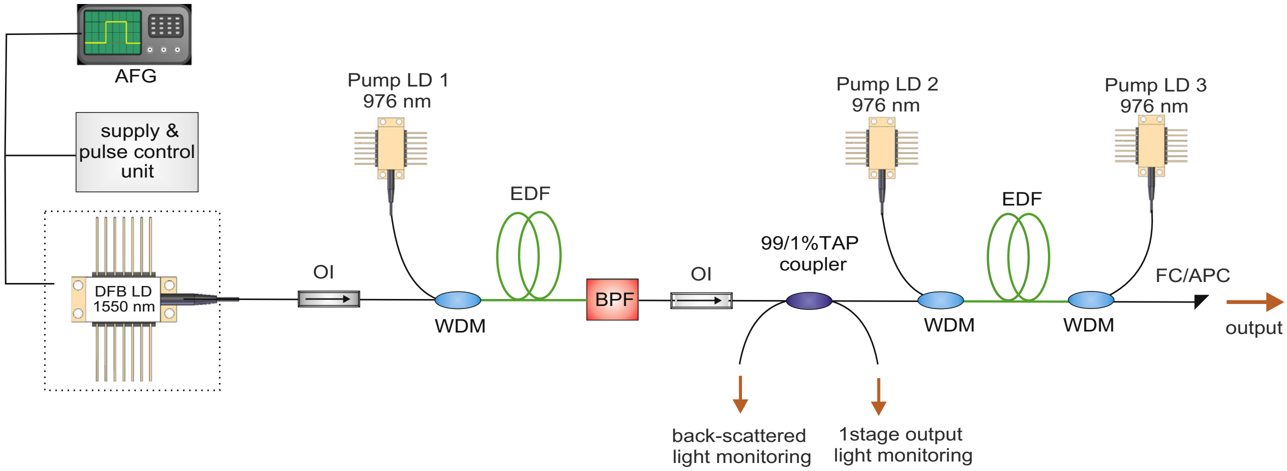

Fig. 1. Experimental MOPA setup. LD—laser diode, AFG—arbitrary function generator, OI—optical isolator, BPF—band-pass filter, WDM—980/1550 wavelength division multiplexer, 99%/1% tap coupler, EDF—erbium-doped fiber.