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High gain erbium-doped fiber amplifier for the investigation of nonlinear processes in fibers

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Abstract

In this work we present a novel design of an optical amplifier with high gain elaborated from erbium-doped fiber (EDF). Its purpose is the amplification of low power pulses from laser diodes. The high power of the output pulses allows the investigation of nonlinear processes in optical fibers. The optical amplifier consists of two stages. The first stage uses a reflective configuration where a signal is amplified twice in the same EDF. The fiber Bragg grating (FBG) was the main element to reflect the signal. The second stage works as a high power amplifier. The input pulse has duration in the range of 1 to 50 ns, with wavelength equal to 1549.1 nm. With input pulse power of 1.5 mW, the amplifier provides 70 W in the output pulse. The gain obtained by the amplifier was 47 dB.

Keywords: Optical amplifiers; Erbium-doped fiber; Fiber optics; Nonlinear optics

1. Introduction

The development of erbium-doped fiber amplifier (EDFA) has revolutionized to optical fiber communications systems. When an EDFA is designed, it is necessary to keep in mind the configuration to use, since it depends on the application of the amplifier. Backward pumping, forward pumping, and bidirectional pumping are typical configurations. EDFAs can be designed as in-line amplifier, pre-amplifier or power amplifier [1]. Optical pulses with small duty ratio or continuous wave (cw) are amplified by power amplifiers [2]. A power amplifier needs several amplification stages [3,4]. High gain is obtained with a reflective configuration, because the signal travels twice through the same EDF [5–8]. Several devices can be used to reflect the optical signal, such as fiber Bragg gratings (FBG), Fiber mirrors, Faraday rotator mirrors [9–12]. A 200 TW of 45 fs was achieved using optical parametric chirped pulse amplification [13]. Multi-kilo-watt with fiber integrated chirped-pulse amplification using air-core photonic bandgap fiber and conventional EDFA was described in [14]. Usually the generation of high peak power pulses relies on mode-locked or Q-switched lasers. However, these lasers are complicated devices, and additionally their use restricts significantly the possibilities to adjust pulse parameters like its duration, and shape. EDFA scheme presented so far in the literature has been developed in the frame of (low-power) telecommunication application, and are thus not designed for high output peak power. In this work, we present a design of EDFA to be used for the investigation of nonlinear processes in optical fibers. It is necessary to mention that the main objective of the amplifier was amplify pulses in the range of 1 to 50 ns from a diode laser for use it as pump pulse power for observation of SRS in a standard fiber and NOLM investigation. The proposed design is easy to elaborate, and it is not as expensive as others, because it has been designed with standard components used in optical fiber communication systems. In this case, pulse duration or shape can be easily modified through adjustment of the diode driving current. We were

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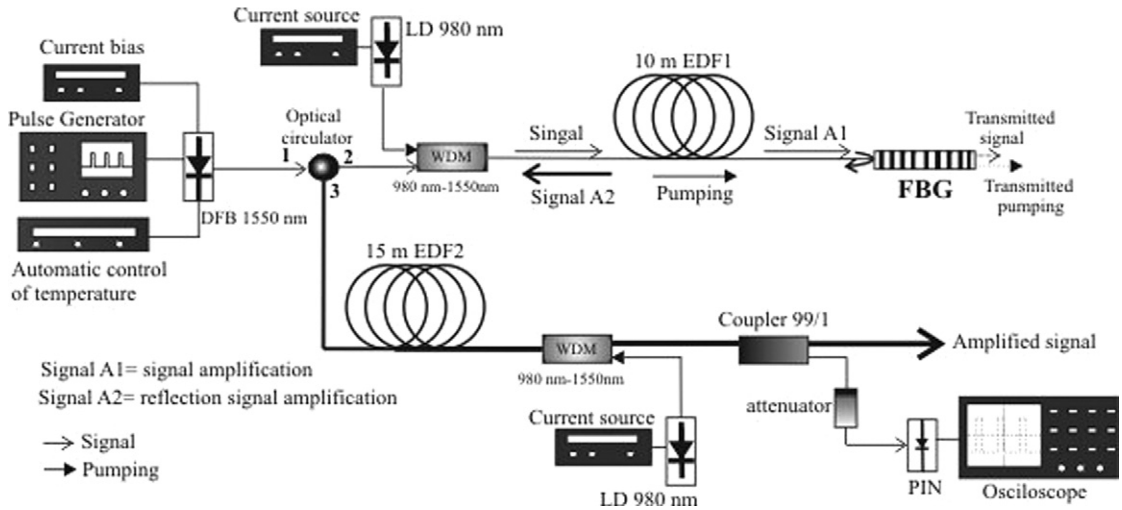

Fig. 1. Proposed design.

concentrated on the application of the amplifier but not in the maximum pulse power that the amplifier could provide. The amplifier consists of two stages, where the first stage used a reflective configuration on signal and the reflection was carried out by a FBG. The FBG reduces significantly the level of amplified spontaneous emission (ASE). With the first stage we were no able to obtain output pulses with desirable powers; therefore we used a second stage in the configuration of a power amplifier [15]. The maximum peak power that we obtained with this design was 70 W at 1.5 mW at the input. With this amplifier we have investigated successfully nonlinear processes in optical fiber such as the operation of a NOLM and SRS [16–23].

2. Experimental setup

Fig. 1 shows the proposed design of the amplifier. It includes two stages: the first stage works in reflective configuration and the second stage works as a power amplifier. The first stage consists of a 10-m long section of erbium-doped fiber (EDF1), a WDM coupler (WDM1) and a FBG. This stage was pumped in the forward configuration. The input signal from a Mitsubishi DFB diode laser ML976H6F is launched to the first stage through an optical circulator, whose typical wavelength is 1550 nm with spectral width (root mean square, RMS) maximum of 3 nm. The same circulator connects the output of the first stage with the second stage of the amplifier. The wavelength of the DFB laser was tuned by changing its temperature so as to match the wavelength of the FBG reflection. We used a Thorlabs stage for cooling. The maximum pulse power at the fiber end of the DFB laser was 1.5 mW. The current threshold of the DFB laser is 10 mA. The repetition frequency of the pulse can be selected over the range 1–1000 Hz.

The Bragg grating central wavelength is 1549.1 nm and its reflection coefficient at this wavelength is ∼100%. The laser temperature should be equal to 13 °C to match this wavelength. If the wavelength of the input signal mismatches the peak reflection wavelength of the FBG, a drastic reduction of the output power appears. The use of a FBG reduces significantly the problem of amplified spontaneous emission (ASE) that is generated by the amplifier because of the narrow bandwidth of reflection.

The second stage consists of a 15-m long EDF (EDF2) and a WDM coupler (WDM1). The pulse in this stage acquires high power. A backward pumping configuration is used. Although in this stage a filter is not introduced to reduce the ASE noise, the amplification obtained for the pulses is enough for our purposes.

Both EDF (1000 ppm Er^{3+} ion concentration) are pumped at 980 nm. The low power attenuation is equal to 3.3 dB/m at 980 nm and 4 dB/m at 1550 nm. The 980 nm laser diode (LD) that we used in the first stage has a maximum pump power of 30 mW, while in the second stage the maximum pump power is 80 mW.

The current pulses driving the DFB laser were generated by a RF pulse generator SRS-DG535. The generator allows current pulses with duration from 1 ns to several hours. Pulses were placed on a 7-mA bias, below the laser current threshold to avoid the generation of a cw component at the laser output, which would saturate the amplifier.

At the output of the amplifier is necessary the use of an isolator to avoid reflections to the amplifier. We used a 99/1% coupler for monitoring. To the 1% port we connected a 30-dB attenuator to reduce even further the pulse power.

The InGaAs photodetector has a 1 GHz bandwidth and the sensibility of the entire system is 3 W/mV, what means that if the response of the oscilloscope is 1 mV, the output power at the output of the amplifier is equal to 3 W. We used a Tektronix TDS3052 with 500 MHz bandwidth oscilloscope.

3. Results and discussion

The amplifier gain was measured against pump power and input pulse power. Fig. 2 shows gain as function of pump power: (a) against pump power of the first stage with a fixed 80 mW pump power in the second stage, (b) against pump power of the second stage with a fixed 24 mW pump power in the first stage. Both graphs were obtained for the same set of values of input pulse powers. We can see that the max-

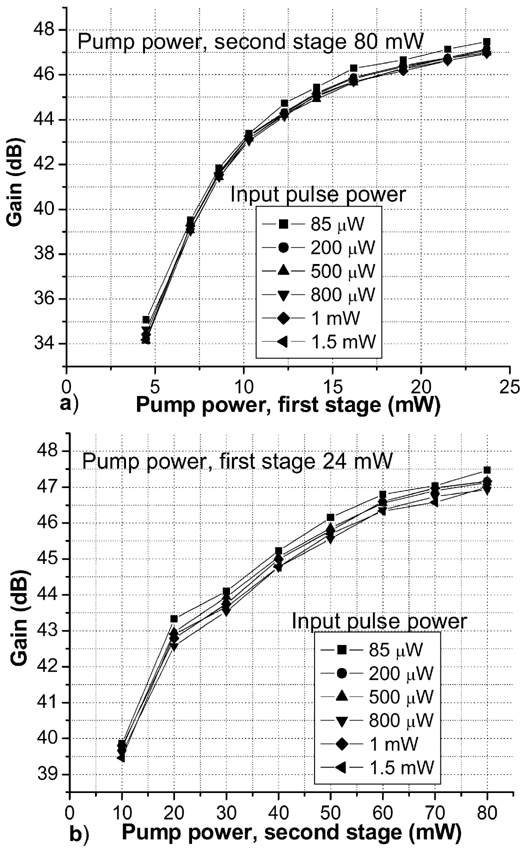

Fig. 2. Amplification against pump power: (a) first stage, (b) second stage.

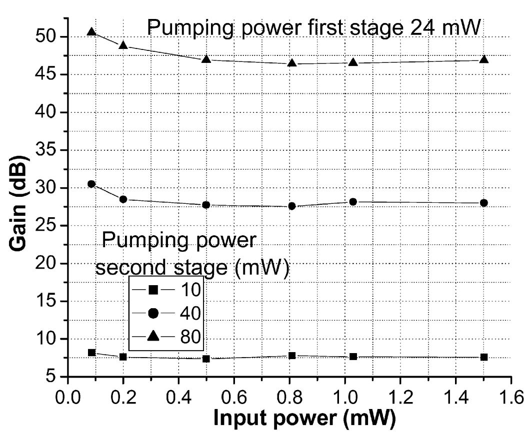

Fig. 3. Gain against input pulse power.

imum gain is 47 dB. The gain was calculated by $G(\mathrm{dB}) = 10\log(P_{\mathrm{sin}}/P_{\mathrm{sout}})$, where P_{sin} is input pulse power and P_{sout} is output pulse power. The maximum input pulse power is 1.5 mW. Note that the amplification does not depend on the input pulse power, because the gain does not show up saturation.

Fig. 3 shows the amplifier gain as a function of input pulse power. A small decrease of the gain is observed when the input pulse power is higher than 200 μW. The slope is more pronounced for higher pump power into the second stage. The gain remains constant in the whole range of the input pulse power. This graph confirms that the amplifier is not in the saturation region. The saturation region of the amplifier is reached when

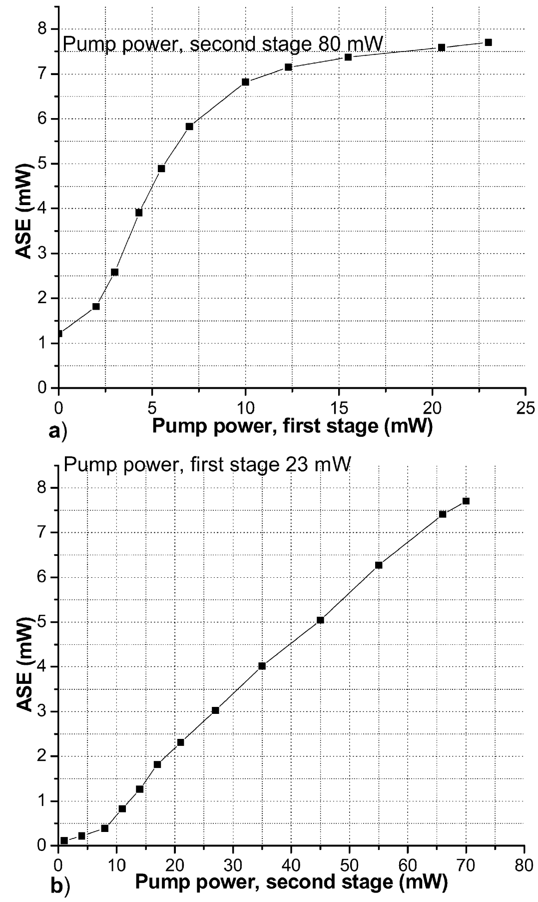

Fig. 4. Output ASE power.

the gain has been reduced by 3 dB with respect to its low input power value.

The maximum output pulse power reached by the amplifier was 70 W for pump powers of 24 and 80 mW in the first and second stages, respectively. The behavior of output pulse power as a function of input pulse power is linear.

The repetition frequency of the signal pulse can be in the range of 1 Hz–1 kHz and the pulse duration of 1–50 ns, without amplification change.

Fig. 4 shows the output ASE as a function of pump power in the first stage with a fixed 80 mW pump in the second stage. (a) The minimum ASE in this case was 1.3 mW which was generated by the second stage when it had the maximum pump power. The maximum ASE power was 8 mW. Its level begins to saturate starting from 12 mW and improving with it the noise figure of the amplifier. (b) When the first stage has maximum pump power, the ASE level was 1 mW, which enters to the second stage. The minimum pump power in the second stage made the ASE level did not amplify and was equal to the graph (a) when the pump power in the second stage was 11 mW.

The ASE that is generated in the first stage is a factor that degrades the development of the power in the second stage of the amplifier. ASE has two components: forward and backward ASE. We eliminate forward ASE using the fiber Bragg grating. Nevertheless the backward ASE passes through the circulator, and enters the second stage of the amplifier. To eliminate this

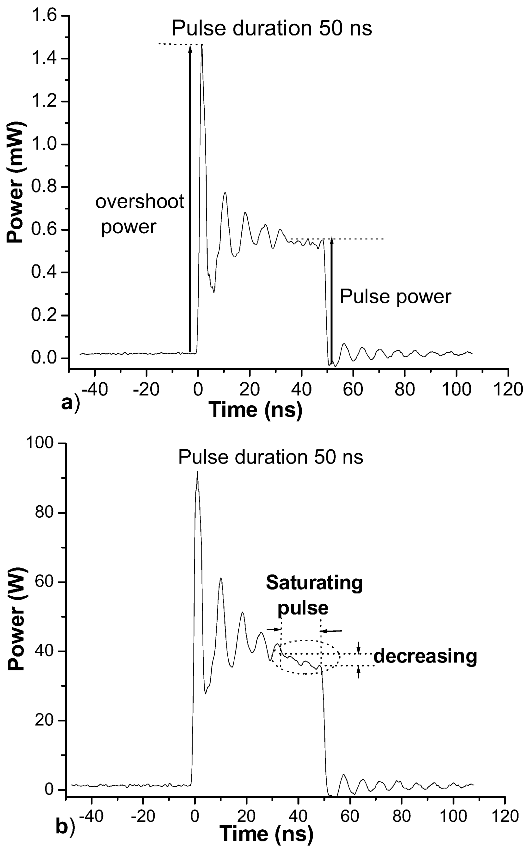

Fig. 5. Pulse shape at the: (a) input pulse, (b) output pulse, of the amplifier with duration of 50 ns.

effect a spectral filter can be used. Nevertheless we obtained sufficient gain for our purposes without spectral filter.

Fig. 5 shows pulse shape at the input and output pulse of the EDFA. The pulse duration is 50 ns with pump power in the first stage of 24 and 80 mW in the second stage of the amplifier. Initially, the pulse has a leading edge overshoot followed by damped oscillations. This effect is produced by our electrical circuit. When the pulse is turned off, damped oscillations are observed too with the same period as in the pulse. The damping disappears after about 35 ns. It is necessary to mention that the overshoot is amplified by the amplifier. Its gain can be higher or equal to the gain of the overall pulse.

The high stimulated emission rate in the amplifier is the reason why the amplifier has a saturation region. With pulses longer than 50 ns will make that it decreases exponentially at the output of the amplifier, due to high stimulated emission in the amplifier.

The DFB laser bias was 7 mA below the laser threshold to avoid cw radiation toward the amplifier, which could saturate it.

Fig. 6 shows the gain as a function of frequency repetition rate of the pulses in the first stage of the amplifier. The measurement was carried out without the FBG at the EDF1 end. In this graph we can see that the gain does not change in the range of 1 Hz–1 kHz. For frequencies above 1 kHz, the gain is decreasing. From 1 kHz up to 10 kHz the gain decreases 1 dB and starting from 10 kHz the gain decreases exponentially down to 14 dB when the repetition rate is 500 kHz. It has to be men-

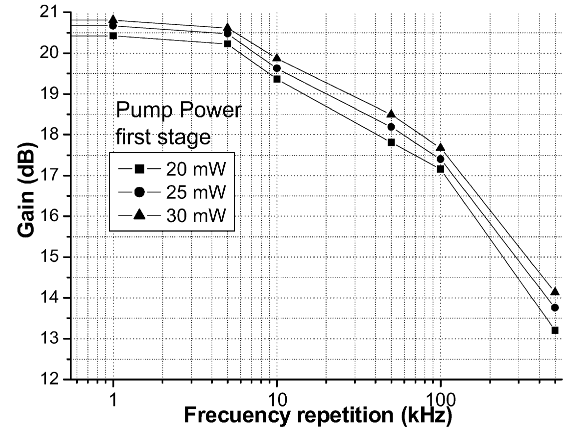

Fig. 6. Gain versus pulse repetition rate for the first stage of the amplifier.

tioned that the gain is decreasing as a function of the frequency in the first stage of the amplifier, therefore if we introduce a signal with higher repetition frequency than 10 kHz to the second stage of the amplifier, it will reach the saturation very soon.

4. Conclusions

In conclusion we have investigated a novel design of an erbium-doped fiber amplifier, using one stage in reflective configuration. It is easy to arm and not expensive. The range of pulse duration is 1–50 ns. The pulse duration or shape can be easily modified through adjustment of the diode driving current. The maximum gain is 47 dB even without spectral filtering of ASE in the second stage of amplification. The maximum output pulse power was 70 W for an input pulse power of 1 mW. We did not find the saturation regime of the amplifier, for this reason we believe that higher input pulse power higher than 1.5 mW could still obtain higher output pulse powers. It is necessary to know that reflections from connections inside the amplifier are factors that it can affect its performance.

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