10 W-level gain-switched all-fiber laser at 2.8 μm

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ABSTRACT

We report a simply designed gain-switched all-fiber laser emitting a maximum average output power of 11.2 W at 2.826 μm. The corresponding extracted pulse energy is 80 μJ at a pulse duration of 170 ns. These performances significantly surpass previous gain-switched demonstrations and are close to the state-of-the-art Q-switched laser performances near 2.8 μm, but with a much simpler and robust all-fiber design. The spliceless laser cavity is made of a heavily erbium-doped fluoride glass fiber and is bounded by fiber Bragg gratings written directly in the gain fiber through the protective polymer coating.

High-power CW and pulsed lasers operating near 3 μm have generated considerable interest in recent years due to their proximity to the fundamental absorption of liquid water [1,2]. The high-power emission centered on the peak absorption of water is particularly appealing for biomedical applications [3], particularly in orthopedics [4], dentistry [5], dermatology [6], and ophthalmology [7]. Powerful and bright fiber lasers operating in the vicinity of 3 μm can also be used as a pump to generate efficient supercontinuum covering the 3–5 μm atmosphere transmission window [8], where various ro-vibrational absorption lines of gas pollutants are resonant [9]. Thus, these laser sources are interesting for short and long-range applications such as gas spectroscopy [10–12] and military countermeasures [13]. For field applications, the laser systems must generally be stable, energetically efficient, compact and, more importantly, robust.

Several pulsed lasers near 2.8 μm, be it mode-locked, Q-switched, or gain-switched have already been demonstrated [14–18]. Antipov et al. recently demonstrated a mode-locked holmium-doped fiber laser with an average power of 327 mW and a peak power of 37 kW (pulse energy of 7.6 nJ) [18]. Tokita et al. reported a Q-switched erbium-doped fluoride glass fiber laser (EDFL) placed in a nitrogen purged enclosure that extracted 12 W of average power and 0.9 kW of peak power (pulse energy of 100 μJ) [15]. Shen et al. recently demonstrated a Q-switched EDFL with an average power of 1.5 W and a peak power up to 1.6 kW (pulse energy of 0.15 mJ) at 10 kHz [19]. Gorjan et al. reported a gain-switched EDFL with 2 W of average power, 68 W of peak power, and 307 ns of pulse duration at 100 kHz [14]. Wei et al. demonstrated the first broadly tunable gain-switched EDFL around 3 μm [20], and Luo et al. reported on the first dual-waveband gain-switched fiber laser emitting around 2 and 3 μm [21]. In all these demonstrations, the cavity design involved free space optics (e.g., lenses, acousto-optic modulators [AOMs], saturable absorbers, isolators, and/or wave plates), which poses reliability and scalability issues for field applications. Among the three pulsed mechanisms described above, gain switching is the only one that can benefit from existing mid-IR fiber components to enable high-power operation in an all-fiber design [22], since it uses pump modulation to generate the laser pulses.

In this Letter, a simple monolithic gain-switched EDFL operating at 2.826 μm is presented with output performances competing with state-of-the-art Q-switched lasers operating near 2.8 μm. With a maximum average output power of 11.2 W (420 W of peak power), a pulse energy of 80 μJ and a pulse duration of 170 ns, the output performances significantly surpass those of previous gain-switched demonstrations in the same wavelength range. These performances are achieved in a robust monolithic laser cavity bounded by intracore fiber Bragg gratings (FBGs) written directly in the gain fiber through the protective polymer coating. The stable operation of the laser is demonstrated over 20 h of continuous operation at high power.

The experimental setup of the gain-switched all-fiber laser is presented in Fig. 1. The linear cavity is made of a heavily (7%) erbium-doped fluoride fiber (Le Verre Fluoré) bounded by two FBGs written using femtosecond pulses and the scanning phase mask technique [23]. Both FBGs are written directly in the erbium-doped fiber core through the protective coating to preserve the integrity and the robustness of the pristine fiber [24]. Moreover, this approach lowers the intracavity losses and simplifies the cavity design by avoiding single-mode fluo-ride fiber splices. Both FBGs have a central wavelength of 2826.0 ± 0.2nm, whereas their spectral width/reflectivities, respectively, are 0.6 nm/90% for the high reflectivity FBG...
(HR-FBG) and 2.2 nm/5% for the low reflectivity FBG (LR-FBG). The transmission spectra of the FBGs, along with the laser signal at different output powers, are presented in Fig. 2. Since the laser emission is controlled by the HR-FBG in this laser configuration, a slight spectral shift of the signal towards longer wavelengths is observed when the pump power is increased. This is due to the thermal expansion of the HR-FBG caused by the high pump absorption at the input end of the doped fiber. Accordingly, the LR-FBG was designed with a broad bandwidth (2.2 nm) to ensure a good spectral overlap at different pump/output powers.

The system is pumped with a high-power fiber-coupled 976 nm laser diode (nLight, element e18) emitting up to 220 W with a spectral width of $\pm 1$ nm. Considering the low duty-cycle operation used in the experiment (below 20%), the central peak wavelength of the diode ranges between 965 and 968 nm, depending on the average pump power. The pump diode is modulated using a fast linear modulator (Messtec Power Converter GmbH, VFM 20-50), which was electronically optimized for the diode to provide a high stability of the pump pulses. The modulator is controlled by a digital pulse generator (Stanford Research Systems, SRS, DG-535). The silica glass pump fiber (200 μm core diameter, 0.22 NA) is spliced directly to an undoped double-clad fluoride glass fiber (Le Verre Fluoré) with a cladding diameter of 250 μm and a NA of 0.46. This multimode splice between the fluoride and the silica fibers was achieved with an iridium filament splicer (Vitran, GPX-3400) using the approach outlined in Ref. [25]. The undoped fluoride glass fiber is then spliced to the erbium-doped fiber (Le Verre Fluoré), which provides gain for the laser cavity. This active fiber has a core diameter of 15 μm with a NA of 0.12 and is doped at 7 mol.% erbium. Its cladding has a 240 × 260 μm double-D shape and is coated with a low-index fluoroacrylate polymer to enable pump guiding. An AlF$_3$ end cap is spliced to the output end of the doped fiber to prevent long-term degradation from the 2.8 μm laser signal, while pro-viding a single transverse mode output beam [26]. To remove any residual pump at the output, a cladding mode stripper was fabricated by recoating the last 5 cm of active fiber with a high-index polymer. A germanium filter also was placed in front of the power detector to remove any signal below 1.9 μm, thus ensuring that only the 2.8 μm signal was detected.

The average power is measured with a thermopile detector (Gentec-EQ, UP19K-50F-W5), while the pump and signal spectra are acquired with grating-based optical spectrum analyzers (Yokogawa, AQ6373B and AQ6376). The pump and signal temporal profiles, respectively, are measured with a 1 ns rise-time Si detector (Thorlabs, FDS010) and a 200 ps rise-time InGaAs detector (ALPHALAS, UPD-5N-IR2-P).

Figure 3 presents a typical pulse train for the pump and signal, as well as their respective temporal profile (inset). For the pump, the peak power was calibrated by applying the maximum operating current to the diode. The signal peak power was calculated from the measured waveform and average power. Throughout the experiment, the pump pulse duration was adjusted for each measurement so that it stops just before the signal pulse is emitted. Such synchronization was critical to achieving the highest average and peak powers from the gain-switched laser in this Letter, while the repetition rate was limited to 140 kHz to prevent the temperature of the erbium-doped fiber at the pump end from exceeding 90°C. With a better limitation for increasing the average output power is the temperature at the pump input end of the heavily erbium-doped fiber. During the experiment, the repetition rate was limited to 140 kHz to prevent the temperature of the erbium-doped fiber at the pump end from exceeding 90°C. With a better...
heat dissipating setup or an optimized fiber design, the repetition rate could be further increased, thus increasing the average output power [22]. In addition, according to the present results, the pulse duration should also decrease, and the peak power should increase.

In the near future, the amplification of the output pulses will be investigated to achieve pulse energies of a few hundred microjoules to enable biomedical applications, particularly for hard tissue cutting, which requires high pulse energies to be efficient [32]. Eventually, high-power supercontinuum generation might also be possible from this amplified source, provided the peak power of the amplified signal is high enough to trigger nonlinear effects in the fiber [8].

To summarize, a monolithic gain-switched EDFL emitting a maximum average output power of 11.2 W with pulse energies up to 80 μJ and a pulse duration as short as 170 ns is demonstrated. The 7.05 W average output power fluctuates by less than 1% over 20 h of continuous operation. These results represent a significant improvement over the previous state-of-the-art gain-switched EDFL from Gorjan et al. [14] and are close to those of the nitrogen purged Q-switched laser from Tokita et al. [15] with a much simpler design. An average efficiency of 28% is obtained, which could be further increased by optimizing the cavity design. A better thermal management of the doped fiber should enable operation at higher repetition rates with higher average output powers. A pump source with higher peak power should also enable the generation of significantly higher peak power pulses with shorter duration. This demonstration is a step towards field applications of pulsed high-power erbium-doped fiber lasers emitting around 3 μm.

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**References**

Fig. 1. Schematic diagram of the monolithic gain-switched erbium-doped fluoride fiber laser emitting at 2826 nm.
Fig. 2. (a) Transmission spectrum of the FBGs and (b) output laser spectra under different operating conditions (140 kHz, 11.2 W; 100 kHz, 7.24 W; 40 kHz, 2.12 W).
Fig. 3. (a) Typical pulse train at 11.2 W output power and 140 kHz repetition rate. The inset shows an example of timing synchronization of the pump and signal pulses, as well as a signal pulse averaged over 60 samples. The signal peak power is evaluated at 420 ± 70 W. (b) Lorentzian fit for each pulse shows the average gain-switched envelope. The average peak power is 345 W with an RMS variation of 3 W.
Fig. 4. Repetition rate effect on the pulse duration (FWHM), energy, and average output power. The pump peak power was set at 210 W.
Fig. 5. Energy, duration, and peak power of the signal pulses as a function of the pump pulse energy and duration, for a fixed repetition rate of 100 kHz. For each point, the pump peak power and duration are adjusted to prevent the onset of a secondary pulse per cycle.
Fig. 6. (a) Laser output power over a period of 20 h. A slight long-term variation of less than 1% of the 7.05 W average power is observed. (b) shows a zoomed view of (a).