Gain-switched Dy\(^{3+}\):ZBLAN fiber laser operating around 3 \(\mu\)m

Lukasz Pajewski\(^1\), Lukasz Sójka\(^1\)✉, Samir Lamrini\(^2\), Trevor M Benson\(^3\), Angela B Seddon\(^3\) and Slawomir Sujecki\(^4\)

\(^1\)Department of Telecommunications and Teleinformatics, Wroclaw University of Science and Technology, Poland
\(^2\)LISA laser products OHG, Max-Planck-Str. 1, Katlenburg-Lindau D-37191, Germany
\(^3\)Mid-Infrared Photonics Group, George Green Institute for Electromagnetics Research, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom

E-mail: lukasz.sojka@pwr.wroc.pl

Keywords: mid infrared fiber laser, dysprosium doped glass, mid infrared sources, pulse fiber laser

Abstract
A gain-switched Dy\(^{3+}\)-doped ZBLAN fiber laser operating at 2.943 \(\mu\)m is experimentally reported for the first time to the best of our knowledge. The laser was pumped by a 1.1 \(\mu\)m Q-switched ytterbium (III) fiber laser constructed in-house. A stable pulse train is achieved with repetition rates spanning between 25 and 100 kHz. For the repetition rate of 50 kHz, stable 183 ns pulses with an energy of 0.72 \(\mu\)J and peak power of 4 W are recorded. By using a longer length of Dy\(^{3+}\)-doped ZBLAN fiber, gain-switched operation was achieved at a wavelength larger than 3 \(\mu\)m.

1. Introduction
Mid-infrared (MIR) fiber laser sources are very important for medicine, sensing and communication [1–3]. This is because many important molecules have strong vibrational transitions in this spectral region. For many applications, like LiDAR, remote sensing or laser surgery, pulsed laser sources are preferred [3]. In recent years significant progress in mid-infrared fluoride fiber lasers has been achieved. Extensive effort has been invested into the development of MIR fiber lasers based on Er\(^{3+}\), Ho\(^{3+}\) doped fluoride glass fibers operating at wavelengths around 3 \(\mu\)m. These lasers can currently generate Watt-level output powers [4–6]. Lately, longer emission wavelengths above 3.5 \(\mu\)m have been presented [7, 8]. For example, a CW (continuous wave) 3.92 \(\mu\)m laser action at room temperature has been observed using Ho\(^{3+}\) doped fluoroindate glass fibers [9].

Also, significant progress in mid-infrared Dy\(^{3+}\)-doped ZBLAN fiber lasers has been achieved in recent years (between 2015 and 2019). The infrared laser action in Dy\(^{3+}\):ZBLAN occurs between the \(^6\)H\(_{13/2}\) upper level and the ground state \(^4\)I\(_{15/2}\) [10]. The highest output power for CW operation of Dy\(^{3+}\):ZBLAN fiber lasers has so far reached 10 W at 3.24 \(\mu\)m under Er\(^{3+}\):ZBLAN pumping at 2.8 \(\mu\)m with a slope efficiency of 58% [11]. Under 1.1 \(\mu\)m pumping, a Dy\(^{3+}\)-doped ZBLAN cavity producing more than 554 mW at 2.98 \(\mu\)m with a slope efficiency of 18% was also demonstrated [12]. Ytterbium (III) ion doped fiber lasers operating at 1.1 \(\mu\)m are commercially available, cost-effective sources. Moreover a tunable Dy\(^{3+}\):ZBLAN fiber laser operating at wavelengths in the range from 2.8 to 3.4 \(\mu\)m was also presented [13]. Further, mode-locked picosecond and femtosecond dysprosium fiber lasers have been reported [14, 15]. Recently, a swept-wavelength (2.8–3.4 \(\mu\)m) Dy\(^{3+}\):ZBLAN fiber laser was used for the real time sensing of ammonia gas [16]. In [16] the authors show that a tunable Dy\(^{3+}\):ZBLAN fiber laser has superior properties when compared with commercially available supercontinuum sources working in this spectral region. It should be also noted that emission from the \(^4\)H\(_{11/2}\) \(\rightarrow\) \(^4\)H\(_{13/2}\) transition at a wavelength of 4.3 \(\mu\)m was observed in dysprosium-doped indium fluoride fiber [17], but laser action has not been demonstrated with this transition yet.

Less attention has been paid to the performance of MIR Dy\(^{3+}\):ZBLAN fiber lasers operating under a Q-switched or gain-switched regime. The first demonstration of a high-energy Q-switched Dy\(^{3+}\):ZBLAN fiber laser was presented in [18]. The laser presented in [18] was able to produce up to 12 \(\mu\)J of energy and durations as short as 270 ns, with variable repetition rates varying from 100 Hz to 20 kHz. In the same contribution the authors also presented a passively Q-switched Dy\(^{3+}\):ZBLAN laser by using a black phosphorus saturable...
A schematic diagram of the experimental set-up is presented in figure 1. The lasing properties of a gain-switched Dy$^{3+}$:ZBLAN glass fiber laser are studied.

The results show that stable pulse widths of 183 ns at the repetition rate of 50 kHz can be produced at the wavelength of around 3.5 μm. In the GS regime the pulse operation is obtained by switching gain on/off by modulating the pump laser. In this approach an extra inter-cavity modulator is not required, which is the main advantage of this technique. Recently, the 10 W-level gain-switched all-fiber Er$^{3+}$:ZBLAN laser operating at 2.826 μm was reported. This laser was able to generate maximum average output power of 11.2 W with pulse energies up to 80 nJ and a pulse duration as short as 170 ns. The longest wavelength achieved from gain switched Er$^{3+}$:ZBLAN was 2.87 μm. Therefore, the development of gain-switched laser with operating wavelength beyond 2.9 μm remains an interesting topic for research.

In this contribution, the lasing properties of a gain-switched Dy$^{3+}$:ZBLAN glass fiber laser are studied. The results show that stable pulse widths of 183 ns at the repetition rate of 50 kHz can be produced at the wavelength of 2.943 μm from a Dy$^{3+}$:ZBLAN laser pumped by a Q-switched 1.1 μm fiber laser. By increasing the fiber length gain-switching was also achieved at a wavelength of 3.002 μm. It is believed that this is the first experimental demonstration of a gain-switched Dy$^{3+}$:ZBLAN fiber laser, the feasibility of which was predicted in [19].

The paper is divided into four sections. After this introduction, section 2 describes the experimental set-up, which was used to obtain MIR gain-switched laser action from the Dy$^{3+}$: ZBLAN fiber. In section 3 the results obtained are presented and discussed. Finally, conclusions are drawn in section 4.

2. Experimental set-up

A schematic diagram of the experimental set-up is presented in figure 1. A home built single transverse mode Q-switched ytterbium all-fiber laser emitting at 1.1 μm was used as a pump source. The Q-switched ytterbium (III) fiber laser consists of double-clad Yb$^{3+}$ fiber (5/130 μm PM-YDF-5/130-VIII Nufern), a fiber coupled acousto-optic modulator (AOM) Gooch and Housego S-M150-0.4C2G-3-F2S, which was driven by an AOM Driver 2910 and controlled by a function generator (GW INSTEK GFG-3015). The laser was able to operate stably with variable repetition rate ranging from 25 to 100 kHz. The fiber had a 1000 ppm core doping concentration of Dy$^{3+}$ (Le Verre Fluoré, France), a core diameter of 15 μm and single mode operation for wavelengths above 2.5 μm. The laser cavity was formed by butt coupling one end of the fiber with a dichroic mirror (highly reflective, > 98%, for the wavelengths stretching between 2.8 and 3.2 μm and transparent, > 75%, for wavelengths around 1.1 μm), while the other end was butt-coupled with a 50% or 70% reflector (for the signal wavelength only), which acted also as an output coupler. The launching efficiency obtained was around 55%–60%. A similar cavity set-up for continuous-wave (CW) operation was investigated in [12].

The output from the fiber laser was collimated using a CaF$_2$ lens with f = 25 mm (110–5105E Eksma Optics). The pump wavelength was removed by an optical filter with a cut-on wavelength of 2.4 μm (Edmund Optics #68–659). The average output power was measured using a thermal power sensor (S401C Thorlabs). The 1.1 μm pulses were measured by using a Si (Thorlabs PDA10A–EC) photodetector with a rise time of < 2.3 ns, while the 3 μm pulses were monitored using an MCT (PVI-4TE-5 Vigo Systems) photodetector with a quoted bandwidth of 17 MHz (rise time of 20 ns). Time evolution of the pulse trains was recorded using a

![Figure 1. Schematic diagram of the gain-switched Dy$^{3+}$:ZBLAN glass fiber laser.](image-url)
digital oscilloscope (Keysight DSO 90804 A) with 8 GHz bandwidth. The emission spectrum generated by the fiber laser in the spectral range between 2.5 and 3.5 μm was monitored using a 150 mm optical monochromator (MSH-150 LOT-Quantum Design GmbH) with a diffraction grating blazed at 4 μm and with a coupled MCT detector (PVI-4TE-5).

3. Results

To construct a fiber laser 0.9 m of Dy\(^{3+}\) doped ZBLAN glass fiber was used. This fiber length should provide around 23 dB pump absorption. The pump absorption was calculated taking into account the pump absorption cross-section at 1.1 μm (\(\sigma_{\text{pump}} = 3.0 \times 10^{-25} \text{ m}^2\)) and a Dy\(^{3+}\) concentration of 1000 ppm (1.815 × 10\(^{25}\) m\(^{-3}\)). The maximum launched power used in this experiment was 534 mW. Stable gain-switched operation of the Dy\(^{3+}\):ZBLAN fiber laser was observed at the launched pump power \(P_L\) of 352 mW (see figure 2). The measured pulse width was 443 ns. Figure 2 shows that when the pump power increases the signal pulse width decreases. Moreover, with increased pump power the time delay between the pump and signal pulses attributed to the buildup time decreases. This behavior is typical of a gain-switched laser [23–26]. It should also be noted that, although the input pump pulse has a multipeak shape, the mid-infrared pulses generated by the Dy\(^{3+}\):ZBLAN fiber laser have a near-Gaussian shape. Thus, the output pulse shape is independent of the pump pulse shape. The input pump pulse duration varies between 410 and 511 ns whilst the output pulse width achieves 183 ns at the pump power of 534 mW. The gain switched pulse RMS (root mean square) amplitude fluctuation was estimated to be 5%, whereas the pump laser RMS amplitude fluctuation was less than 1%.

Figure 3 shows an enlarged temporal profile of the shortest output pulse with 183 ns duration, recorded for the launched pump power of 534 mW at a 50 kHz repetition rate. It should be pointed out that this is the shortest pulse duration observed, to the Authors’ knowledge, for a Dy\(^{3+}\):ZBLAN fiber laser operating in a Q-switched or gain-switched regime. It is well known that the pulse duration in a gain-switched laser depends on the cavity round-trip time [26]. For a 0.9 m long active fiber, the calculated round-trip time is around 9–10 ns. Thus it can be expected that pulses shorter than 183 ns can potentially be obtained from a gain-switched Dy\(^{3+}\):ZBLAN laser in the near future.

Figure 4 presents examples of pulse trains recorded at different repetition rates of 25, 50 and 100 kHz. These results were achieved by changing the repetition rate of the 1.1 μm pump laser. The results shown in figure 4 confirm that the gain-switched Dy\(^{3+}\):ZBLAN fiber laser can operate stably for a broad range of repetition.
frequencies. Additionally, it is noted that the results from figure 4 are in good agreement with the modeling result presented in \[19\], which predicted that a gain switched Dy$^{3+}$:ZBLAN fiber laser is capable of operating from 10 kHz up to 140 kHz.

Figure 5 shows the dependence of the measured average laser output power on the average launched pump power. A 12% slope efficiency and 35 mW maximum output power were obtained for a cavity with 98.5%–50% facet reflectivities. The measured slope efficiency of the 12% is slightly lower than that previously reported for a similar laser cavity operating in a CW regime (which had a slope efficiency of 18%) \[12\].

Figure 6 presents the emission spectrum generated by the gain-switched fiber laser for a launched pump power of 534 mW and a 0.9 m fiber length. These results show that the laser operated at 2.943 μm with a full width half maximum (FWHM) bandwidth of 10 nm.

The measured RF (radio frequency) spectrum of the gain-switched fiber laser at a launched pump power of 534 mW and a repetition rate of 50 kHz is presented in figure 7. The SNR (signal to noise ratio) of the RF spectrum is 61.31 dB, which indicates the good quality operation of the Dy$^{3+}$:ZBLAN gain-switched laser at a single repetition rate frequency.

### 3.1. Gain-switched operation beyond 3 μm

In order to achieve laser operation beyond 3 μm, a longer fiber length of around 1.4 m was used in the laser experiment. The calculated pump absorption for this fiber length is equal approximately to 33 dB. The maximum launched power in this experiment was 1.2 W. A Dy$^{3+}$:ZBLAN fiber laser operating around 3 μm is a quasi-three level laser. In a free running regime, the lasing wavelength strongly depends on the fiber length. By increasing the fiber length the re-absorption is enhanced and laser gain tends to shift towards longer

---

**Figure 3.** The temporal profile of the shortest stable output pulse of Dy$^{3+}$:ZBLAN gain switched laser recorded for a launched pump power of 534 mW at 50 kHz repetition rate. The fiber length used in this experiment was \(L = 0.9\) m.

**Figure 4.** Pulse trains of gain-switched the Dy$^{3+}$:ZBLAN fiber laser at different pump repetition rates of 25, 50, 100 kHz. The fiber length used was \(L = 0.9\) m.
Therefore, by increasing the fiber length the laser operating wavelength moves towards longer wavelengths [27]. The laser design used in this experiment is almost the same as the one presented in figure 1. The only difference is that the output coupler mirror has 70% reflectivity for the signal wave. Figure 8(a) shows the single pulse waveforms recorded for a launched pump power of 1.2 W and a repetition rate of 50 kHz. The measured pulse duration at 3.002 μm was 492 ns, with an average output power of 80 mW. This corresponds to a pulse energy of 1.6 μJ and a peak power of 3.25 W. Figure 8(b) presents the emission spectrum generated by the gain-switched laser for a launched pump power of 1.2 W and a 1.4 m fiber length. The results shown in figure 8(b) confirm that the laser operates at 3.002 μm with a FWHM bandwidth of approximately 15 nm.

4. Conclusions

To the best of the authors’ knowledge, in this paper the first demonstration of gain-switched operation of MIR Dy³⁺:ZBLAN fiber laser is reported. The developed laser was pumped by a Q-switched 1.1 μm fiber laser. The gain-switched Dy³⁺:ZBLAN fiber laser operating at 2.943 μm was able to produce pulse widths of 183 ns and peak powers up to 4 W at a 50 kHz repetition frequency. Additionally, gain switched operation was also achieved at a wavelength of 3.002 μm by using a longer fiber length. The generated pulses have 492 ns width. The presented experimental results have demonstrated that gain-switching is a reliable method of producing pulses
with hundreds nanosecond duration from $\text{Dy}^{3+}:\text{ZBLAN}$ fiber laser with an operating wavelength of approximately $3 \, \mu\text{m}$.

**Acknowledgments**

This work was supported support from Designated Subsidy for Young Scientist ‘Młoda Kadra’ and partially by the Faculty of Electronics, Wrocław University of Science and Technology (049U/0032/19). L Pajewski and L Sojka equally contributed to this work.

**ORCID iDs**

Lukasz Sójka @ https://orcid.org/0000-0003-1665-313X

**References**

[1] Jackson S 2012 Towards high-power mid-infrared emission from a fibre laser *Nat. Photon.* **6** 423–31
[2] Falconi M C, Laneve D and Prudenzano F 2017 Advances in Mid-IR Fiber Lasers: tellurite, fluoride, and chalcogenide *Fibers* **5** 23
[3] Zhu X, Zhu G, Wei C, Kotov L, Wang J, Tong M, Norwood R and Peyghambarian N 2017 Pulsed fluoride fiber lasers at $3 \, \mu\text{m}$ [Invited] *J. Opt. Soc. Am. B* **34** A15–28
[4] Zhu X and Jain R 2008 Watt-level 100 nm tunable $3 \, \mu\text{m}$ fiber laser *Photon. Technol. Lett.* **20** 156–8
[5] Fortin V, Bernier M, Bah S T and Vallee R 2015 30 W fluoride glass all-fiber laser at $2.94 \, \mu\text{m}$ *Opt. Lett.* **40** 2882–5
[6] Aydin Y O, Fortin V, Vallée R and Bernier M 2018 Towards power scaling of 2.8 μm fiber lasers Opt. Lett. 43 4542–5
[7] Bawden N, Matsukuma H, Henderson-Sapir O, Klatsstaya E, Tokita S and Ottaway D J 2018 Actively Q-switched dual-wavelength pumped Er3+: ZBLAN fiber laser at 3.47 μm Opt. Lett. 43 2724–7
[8] Henderson-Sapir O, Jackson S D and Ottaway D J 2016 Versatile and widely tunable mid-infrared erbium doped ZBLAN fiber laser Opt. Lett. 41 1676–9
[9] Maes F, Fortin V, Poulain S, Poulain M, Carrée J Y, Bernier M and Vallée R 2018 Room-temperature fiber laser at 3.92 μm Optica 5 761–4
[10] Quimby R and Saud M 2017 Anomalous nonradiative decay in Dy-doped glasses and crystals Opt. Lett. 42 117–20
[11] Fortin V, Jobin F, Larose M, Bernier M and Vallée R 2019 10 W-level monolithic dysprosium-doped fiber laser at 3.24 μm Opt. Lett. 44 491–4
[12] Sójka L, Pajewski L, Popenda M, Beres-Pawlik E, Lamrini S, Markowski K, Osuch T, Benson T M, Seddon A B and Sujecki S 2018 Experimental investigation of mid-infrared laser action from Dy3+ doped fluorozirconate fiber IEEE Photon. Technol. Lett. 30 1083–6
[13] Majewski M, Woodward R and Jackson S 2018 Dysprosium-doped ZBLAN fiber laser tunable from 2.8 to 3.4 μm, pumped at 1.7 μm Opt. Lett. 43 971–4
[14] Woodward R I, Majewski M R and Jackson S D 2018 Mode-locked dysprosium fiber laser: picosecond pulse generation from 2.97 to 3.30 μm APL Photon. 3 116106 –10
[15] Wang Y, Jobin F, Duval S, Fortin V, Laporta P, Bernier M, Galzerano G and Vallée R 2019 Ultrafast Dy3+:fluoride fiber laser beyond 3 μm Opt. Lett. 44 395–8
[16] Woodward R I, Majewski M R, Hudson D D and Jackson S D 2019 Swept-wavelength mid-infrared fiber laser for real-time ammonia gas sensing APL Photon. 4 020801–1–7
[17] Majewski M R, Woodward R I, Carree J Y, Poulain S, Poulain M and Jackson S D 2018 Emission beyond 4 μm and mid-infrared lasing in a dysprosium-doped indium fluoride (InF3) fiber Opt. Lett. 43 1926–9
[18] Woodward R I, Majewski M R, Macadam N, Hu G, Albrow-Owen T, Hasan T and Jackson S D 2019 Q-switched Dy3+:ZBLAN fiber lasers beyond 3 μm: comparison of pulse generation using acousto-optic modulation and inkjet-printed black phosphorus Opt. Express 27 15032–45
[19] Falconi M C, Laneve D, Bozzetti M, Fernandez T T, Galzerano G and Prudenzenz F 2018 Design of an efficient pulsed Dy3+: ZBLAN fiber laser operating in gain switching regime J. Lightwave Technol. 36 5327–33
[20] Jobin F, Fortin V, Maes F, Bernier M and Vallée R 2018 Gain-switched fiber laser at 3.55 μm Opt. Lett. 43 1770–3
[21] Paradis P, Fortin V, Aydin Y O, Vallée R and Bernier M 2018 10 W-level gain-switched all-fiber laser at 2.8 μm Opt. Lett. 43 3196–9
[22] Luo H, Yang J, Liu F, Hu Z, Xu Y, Yan F, Peng H, Ouelfette F, Li J and Liu Y 2019 Watt-level gain-switched fiber laser at 3.46 μm Opt. Express 27 1367–75
[23] Wei C, Luo H, Shi H, Lyu Y, Zhang H and Liu Y 2017 Widely wavelength tunable gain-switched Er3+:doped ZBLAN fiber laser around 2.8 μm Opt. Express 25 8816–27
[24] Luo H, Li J, Hai Y, Lai X and Liu Y 2018 State-switchable and wavelength-tunable gain-switched mid-infrared fiber laser in the wavelength region around 2.94 μm Opt. Express 26 63–79
[25] Luo H, Li J, Zhu C, Lai X, Hai Y and Liu Y 2017 Cascaded gain-switching in the mid-infrared region Sci. Rep. 7 16891
[26] Swiderski J, Maciejewska M, Kwaśniewski J and Marnálek M 2013 An all-fiber, resonantly pumped, gain-switched, 2 μm Tm-doped silica fiber laser Laser Phys. Lett. 10 015107
[27] Majewski M R and Jackson S D 2016 Highly efficient mid-infrared dysprosium fiber laser Opt. Lett. 41 2173–6