Development and applications of gain-switched fiber lasers [Invited]

Jianlong Yang, Yulong Tang, and Jianqiu Xu*

Key Laboratory for Laser Plasmas (Ministry of Education) and the Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China
**Corresponding author: jqxu09@sjtu.edu.cn*

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We briefly review the development of gain-switched rare-earth-doped fiber lasers and their applications in wavelength conversion to mid-IR, supercontinuum generation, and medicine in recent years. We illustrate the similarities between gain-switching and Q-switching techniques that will provide tools for the design and optimization of the gain-switched fiber lasers. From the nature of the gain-switched fiber lasers, benefits of this kind of lasers to 2-μm region and in-band-pumped (two-level system) laser systems are obvious. Advantages of in-band-pumped 2-μm lasers are discussed and analyzed with a simple numerical simulation in terms of Tm-doped fiber lasers. We also propose the key factors in the development of the gain-switched fiber lasers and predict the future tendency.

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1. INTRODUCTION

In the pulsed fiber laser regime, gain-switching is an alternative technique to generate a high-repetition-rate pulse train with nanosecond pulse duration besides Q-switching and external modulation of a continuous-wave (CW) laser. Compared to conventional solid-state bulk lasers, realization of the gain-switched operation is convenient in the regime of rare-earth-doped fiber lasers due to their high optical gain. Consequently, the gain-switched fiber lasers have drawn extensive interest and been well developed in recent years [1–3]. Especially for fiber lasers operating at wavelengths around 2 μm, gain-switching rather than direct modulation of a laser diode (LD) (which has low efficiencies at wavelengths longer than 1.8 μm because of Auger recombination [4]) is the preference for pulsed lasers or the seeder to master oscillator power amplifier (MOPA) fiber lasers. As a kind of fiber lasers, gain-switched fiber lasers have all the general advantages of fiber lasers, such as single-mode operation, high efficiency, and being maintenance-free [5]. Furthermore, several other features establish an important role of gain-switched fiber lasers in the fields of laser research, application, and commercialization, as summarized below:

- Simple geometry. Unlike Q-switching and CW laser modulation, gain-switching does not need additional in-cavity components, which is convenient for realizing all-fiber configurations of gain-switched fiber lasers and compact system designs.
- High pulse energy. Without restrictions of the damage thresholds of the in-cavity components, the pulse energy is only limited by the core area of the doped fiber. As a result, it can be scaled to a much higher level than that of other pulse generation techniques. For Tm-doped fiber lasers without further amplifier stages, pulse energy up to 14.7 mJ has been reported [6].
- Wide spectral coverage. Gain-switching has been applied to almost every rare-earth cation used in fiber lasers: Nd^{3+} [1], Tm^{3+} [2,3,6,7], Er^{3+} [8–10], Yb^{3+} [10–12], Ho^{3+} [13,14]. The corresponding wavelengths vary from near-IR (845 nm) to mid-IR (2.7 μm).
- Narrow bandwidth. Using fiber Bragg gratings (FBGs), gain-switched fiber lasers can acquire laser pulses with spectral bandwidths of less than one nanometer [12,14,15]. The chirp-free operation of the gain-switched fiber lasers makes them suitable for applications, such as Doppler lidar [14] and nonlinear frequency conversion [12].

In this paper, we briefly review and summarize the development and progress made to date toward gain-switched fiber lasers and their applications in wavelength conversion to mid-IR, supercontinuum generation, and medicine. In Section 2, we introduce the gain-switched fiber lasers and illustrate their physical processes, which are compared to Q-switching for more explicit understanding. We summarize and discuss the state-of-the-art results in Section 3. In Section 4, we illustrate the applications of gain-switched fiber lasers and discuss the key factors that will influence their future uses. Finally, we draw our conclusions in Section 5.

2. BASIC PRINCIPLE

Figure 1 shows the typical configuration of an all-fiber gain-switched fiber laser, in which it is evident that gain-switched fiber lasers generally have an extremely simple geometry. Usually, a pulsed pump source has a pigtail output and the pump light couples into the core of gain fiber directly for better absorption. (Because the rare-earth-doped fibers have large absorption cross sections at pump wavelengths and available high-power LDs, such as Tm-doped silica fiber at ~793 nm, a cladding-pumped scheme can also be employed

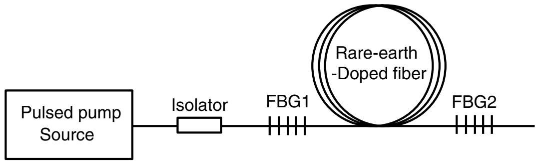

Fig. 1. Basic setup of an all-fiber gain-switched fiber laser.

with double-cladding fibers. In this approach, due to the mismatch of the pump and gain fibers, a fiber combiner rather than an isolator is needed.) A pair of FBGs provide the feedback, in which FBG1 has a high reflectivity at the wavelengths of the laser, equivalent to the high-reflectivity mirror in traditional lasers, and FBG2 has a low reflectivity, equivalent to the output coupler. A fiber isolator is employed to protect the pump source from the backward reflection of FBGs. A rare-earth-doped fiber is often heavily doped to achieve a high optical gain and shorten the length of the gain medium, which has a strong impact on the performance of gain-switched fiber lasers, as discussed below. The all-fiber structure is attributed to the development of high-power LDs and FBGs in recent years, which replaced the solid-state lasers and dichroic mirrors employed in early years [2,7,8]. However, the available peak power from a pulsed LD is still limited, which largely affects the achieved pulse energy [3]. In addition, manipulation of the polarization state of the output laser can easily be realized by using polarization-maintaining fibers [16–18]. Gain-switching has also been demonstrated in a ring-cavity configuration [19].

We found a similarity in physical processes between gain-switching and Q-switching, as illustrated in Fig. 2. The upper panel in Fig. 2 shows the evolution of their upper laser level populations during a single pulse generation, and the lower panel shows the corresponding emitting characteristics. The “pump interval” is the width of the pump pulse in gain-switching, and is the CW pump duration before the cavity loss/quality factor is switched in Q-switching (the switching process can be realized actively and passively; see the general introduction in [20]). We assumed here that the pump pulse in gain-switching has a squared shape and the gain-switched and Q-switched operations have the same pump rate. As shown in the figure, the pump power excited the rare-earth-doped ions to their upper laser level, so the population increased exponentially. Before reaching the laser threshold, the processes

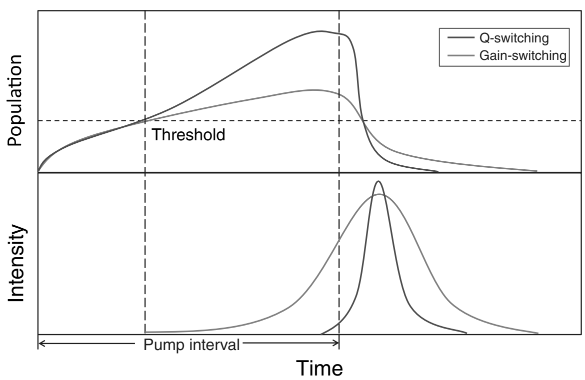

Fig. 2. Schematic illustration of the difference between gain-switching and Q-switching. The upper panel shows the evolution of their upper laser level populations during a single pulse generation, and the lower panel shows the corresponding emitting characteristics.

in gain-switching and Q-switching are identical. When they reach the threshold, the gain-switched lasers start to lase while the Q-switched lasers keep silent, accumulating their upper level population exponentially. However, due to the effect of the pump pulse, instead of decreasing by the formed laser, the upper level population in gain-switching also increases, in a relatively slow trend. The increase in the upper level population stops until the end of the pump pulse in gain-switching, and the cavity loss/quality factor is switched in Q-switching. After that, the upper level populations are consumed rapidly and the lasers keep growing. The lasers reach their peak when the populations go back to the threshold. Then the emissions keep weakening, because stimulated absorption rather than stimulated emission dominates, and the laser pulses form.

The similarities between the two operations make it possible that the theories and formulas developed for Q-switching [20,21] can also be applied in gain-switching in general. The experience in the design and optimization of Q-switched lasers will benefit the counterpart of the gain-switched fiber lasers. For example, the pulse width of Q-switching can be expressed as [20]

$$t_p = \frac{2(n_i - n_f)l}{n_i c - n_t[1 + \ln(n_i/n_t)]c}, \tag{1}$$

where n_i and n_f are the initial and final inverse population densities, respectively. n_t is the inverse population density at the threshold. l is the length of the resonator cavity, and c is the velocity of light in vacuum. In the case of gain-switching, although this equation seems to be a good approximation only when the pump pulses have high peak powers and short widths, the phenomenon where the pulse width is roughly in direct proportion to the cavity length has been observed in gain-switched fiber lasers [3,22]. However, a specific theoretical model and quantitative analysis are also desired for gain-switched lasers.

Another important issue relating to the physics process that should be stressed is the influence of the lifetime of the pump absorption level on the temporal characteristics of the gain-switched fiber lasers; we use a simple numerical simulation on a gain-switched Tm-doped fiber laser to clarify it. In the left panel of Fig. 3, we have illustrated a simplified energy diagram of Tm^{3+} ions. Different pump schemes and their corresponding transitions are represented by black arrows, and the red arrow is the laser transition. The lifetime of each excited level is also indicated; we used the data in [23]. To make the results striking, we ignored processes such as excited state absorption (ESA) and cross relaxation (CR), which are abundant in this system and certainly have an impact on the temporal features. We considered the stimulated absorption of the pump power at different wavelengths, the simulated and spontaneous emissions of the laser, and the nonradiative decay of each excited level. A set of rate equations can be deduced in the form

$$\frac{\partial N_4}{\partial t} = W_{14}N_1 - \frac{N_4}{\tau_4}, \tag{2}$$

$$\frac{\partial N_3}{\partial t} = W_{13}N_1 + \frac{N_4}{\tau_4} - \frac{N_3}{\tau_3}, \tag{3}$$

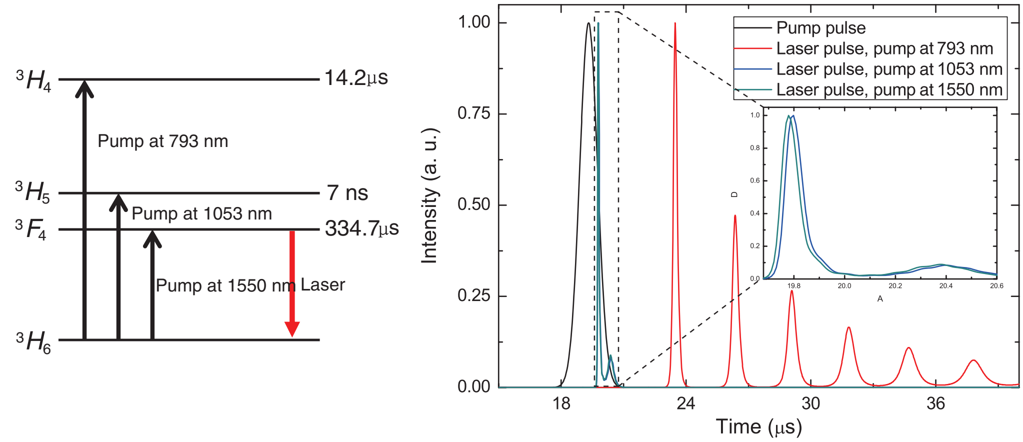

Fig. 3. Left panel is the simplified energy diagram of Tm^{3+} ions; different pump schemes and their corresponding transitions are represented by black arrows, and the red arrow is the laser transition. Right panel is the temporal features of a numerical simulation on a gain-switched Tm-doped fiber laser. To demonstrate the detailed information of the pulses induced by the pump wavelengths at 1053 and 1550 nm, we enlarged the content inside the dashed line box.

$$\frac{\partial N_2}{\partial t} = W_{12}N_1 + \frac{N_3}{\tau_3} - \frac{N_2}{\tau_2} - W_{21}N_2, \tag{4}$$

$$N_1 = N_{Tm} - N_4 - N_3 - N_2, \tag{5}$$

where N_1, N_2, N_3, and N_4 correspond to the populations on $^3H_6$, $^3F_4$, $^3H_5$, and $^3H_4$. τ_2, τ_3, and τ_4 are the lifetimes of excited levels $^3F_4$, $^3H_5$, and $^3H_4$, respectively. N_{Tm} is the doping concentration of Tm^{3+} ions, and t represents time. The expressions of the stimulated absorption and emission coefficients $W_{ij}(ij = 12, 13, 14, 21)$ are the same as in [24], which is the work on the gain-switched Er/Yb-codoped fiber lasers. We also used the optical power propagation equations of that paper here to describe the behavior of pump and laser lights in fiber. The parameters employed in the simulation are from [23,24], except that we set the Tm-doped fiber with a doping concentration of 1×10^{26} m^{-3} and a length of 10 m. The simulation results are shown in the right panel of Fig. 3. The black line illustrates the input pump pulse with a Gaussian profile, and the red, blue, and green lines are the output 2-μm pulses at the pump wavelengths of 793, 1053, and 1550 nm, respectively. They were all pumped by pump pulses with pulse energies 5 times larger than the thresholds. We can find from the results that the 793-nm pump has evident differences from the others, which could be attributed to the much longer relaxation time of $^3H_4 \rightarrow {}^3F_4$ (~14.2 μs) than that of $^3H_5 \rightarrow {}^3F_4$ (7 ns). The blue and green pulses have almost the same temporal profile, suggesting that the nanosecond relaxation time can be neglected by the gain-switched fiber lasers. It is worth noting that the blue and green pulses also do not have a clearly single-peaked profile. We found that this phenomenon emerged when the pump pulse energy was high, which may be explained by the fact that the residual pump energy stored in the gain medium could drive the upper level population above the threshold again after the emission of the first gain-switched pulse.

3. PROGRESS OF GAIN-SWITCHED FIBER LASERS

Since the early investigation of a gain-switched Nd-doped fiber laser in [1], this technique has been explored and developed for two decades. In Table 1, we list the results of primary experiments on gain-switched fiber lasers with different rare-earth-doped fibers and pump schemes during these years, in which the arrangement is roughly based on

Table 1. Reported Output Features of the Gain-Switched Fiber Lasers

Fiber Type	Pump λ (nm)	Laser λ (nm)	Pulse Energy (mJ)	Slope Efficiency (%)	Pulse Widths (ns)	Repetition Rates (kHz)	References
Nd-doped silica	590	1060	1.84×10^{-6}	32 (57)	40	2500	[1]
Tm-doped silica	1064	1840–1940, 2000, 2040	14.7	40 (71)	330	–	[2,6]
Tm-doped silica	790	1909–2018	10.1	30 (74)	300	–	[7]
Er-doped ZBLAN	791	2700–2770	1.9	13.5 (47)	200	–	[8]
Er/Yb-codoped silica	900	1040–1046, 1535–1541	1.38	15 (17)	–	–	[10]
Tm-doped silica	1550	1990, 2000, 2044	0.035	50 (65)	10	500	[3,16]
Er-doped fluoride	974 + 1550	845	0.002	–	2440	200	[9]
Yb-doped silica	965	1080	0.036	36 (40)	770	50	[11]
Yb-doped silica	915	1064	0.15	60 (70)	200	210	[25,26]
Ho-doped silica	1909	2106	0.003	44 (49)	150	80	[13]
Tm-doped silica	1914	1940, 2020	10	80 (81)	61	50	[27,28]
Ho-doped silica	1950	2104, 2112	0.016	65 (70)	38	600	[17]
Ho-doped fluoride	1150	2074	0.006	4.8 (9)	460	30	[29]
Tm-doped silica	790 + 1053	2018	2	29.1 (74)	390	100	[15,18]

the chronological order. The pulse energies and slope efficiency are the maximum values in those works, while the pulse widths are the minimum values. We also listed the efficiencies in which the quantum defect has been subtracted (slope efficiency/quantum efficiency). They are inside the parentheses next to the slope efficiencies. In the early years, researchers employed flash lamp-pumped solid-state lasers, such as Nd:YAG and Ti:sapphire, to serve as the pump sources of the gain-switched fiber lasers [2,6,7,10]. The merit of such devices is that the high energy pulses they provided can scale the output of the gain-switched fiber lasers to a high level directly. We find in Table 1 that several developed lasers can directly output pulses up to about 10 mJ without further amplification, which will bring convenience to their applications.

Another trend easily noticed is that the majority of the research is on Tm- or Ho-doped fiber lasers, which generate laser radiation at a wavelength range of ~1.8–2.1 μm. The concentration on the 2-μm lasers may be explained by the following factors: (1) the in-band pump can be realized in Tm- and Ho-doped fibers, greatly increasing the efficiency of the gain-switched fiber lasers, (2) nanosecond pulsed lasers with a wavelength as short as 1.8 μm can easily be acquired from the modulated CW LD, (3) high pulse energy can be obtained in the gain-switched lasers at a wavelength of around 2 μm for reasons such as a high stimulation cross section and a large single-mode area, and (4) several applications, especially the wavelength conversion to mid-IR by an optical parametric oscillator (OPO), stir up an urgent need for this kind of pulsed laser source.

The temporal characteristics of gain-switched fiber lasers also deserve our attention, as they impeded the advance of the lasers for several years. At the beginning of the research on the gain-switched fiber laser, the output pulses usually exhibited the features of relaxation oscillation [see Fig. 4(b)] or a train of irregular spikes [6]. The unwanted laser spikes affect conversion efficiencies and uses of the lasers. This phenomenon was thought to be related to the relaxation from the pump absorption level [3], but, as shown by the simulation in the previous section, it cannot explain the fact that the intensities of successive spikes do not weaken gradually in some experiments [2,6]. Other physical processes, such as ESA, CR, and the shape of the pump pulse, are thought to make negligible contributions to this phenomenon. However, they still need to be verified by experiments and numerical simulations. In 2007, Jiang and Tayebati used a 1.55-μm pulsed laser to pump a Tm-doped fiber and realized the in-band pump scheme, which effectively diminished the unwanted spikes and kept the pulse train regular and stable [3]. Moreover, due to the controllable pulse train, the pulse width of output pulses can be narrowed by shortening the gain fiber length based on Eq. (1). The authors have acquired 10 ns gain-switched pulses from a 25-cm long active fiber. Moreover, regarding the in-band pump scheme, this provides another convenience in the development and application of gain-switched Tm- and Ho-doped fiber lasers: the former can be pumped by 1.5-μm LDs with few stages of Er-doped or Er/Yb-codoped fiber amplifiers, and the latter can be pumped further by a 1.9-μm gain-switched Tm-doped fiber laser.

For the rare-earth-doped fiber lasers that are not two-level systems and that bring difficulties to in-band pumping, gain-switched operation is not efficient, due to the slow energy transformation from the pump level to the upper laser level. Several efforts have been made to avoid this dilemma. For example, in a Er-doped fluoride fiber laser, the researchers made use of the cascade transitions $^4S_{3/2} \rightarrow {}^4I_{13/2} \rightarrow {}^4I_{15/2}$ to create gain-switching: a CW 974-nm LD pumps the population to $^4S_{3/2}$, and a pulsed 1550-nm laser depletes the population on $^4I_{13/2}$, so the transition $^4S_{3/2} \rightarrow {}^4I_{13/2}$ can produce gain-switched laser pulses. This method seems delicate and robust, but applying it to other kinds of fibers requires more work.

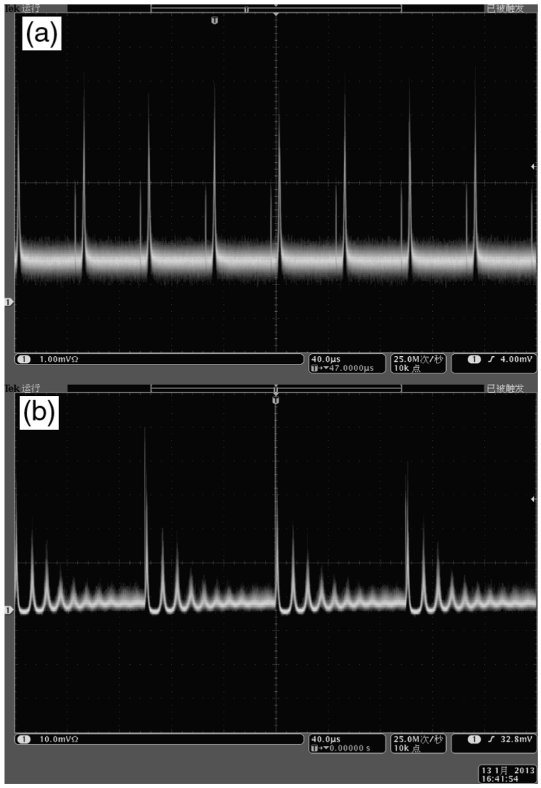

Fig. 4. Temporal characteristics of a gain-switched Tm-doped fiber laser with a hybrid pump scheme: a pulsed 1.5-μm pump source and a CW 793 nm LD pump. (a) and (b) The situations when the launched CW pump power is at a low and a high level, respectively.

Usually, gain-switched fiber lasers require high pump pulse energy. For a Tm-doped fiber with a core diameter of 6.3 μm, pump pulse energy of 8 μJ was needed to achieve laser emission [3]. For fibers with core diameters larger than 15 μm, the thresholds rise to a few millijoules [7,10]. Furthermore, to realize gain-switched operation and scale the output to high levels, the traditional 1.5-μm LD source usually needs to be amplified by more than one or two fiber amplifiers, which greatly increases the complexity of the whole laser system and weakens the advantages of the gain-switched lasers in geometry. To solve this problem, we proposed a hybrid pump scheme that needs a high-power CW LD at 793 (or 808) nm and a pulsed LD (or fiber laser) at ~1 (or 1.5–1.6) μm to serve as the pump sources. The high-power LD first pumps the population close to the threshold, then the pulsed source triggers the laser; meanwhile, the residue of CW power can be used to amplify the generated pulses. Using this approach, we achieved the pulse energy of emission at ~2 μm up to 2 mJ [15], which is comparable to that generated from a gain-switched laser pumped by solid-state bulk lasers. Another advantage of this approach is the temporal features. Due to the fact that the laser is triggered by a 1 or 1.5-μm pump source, which is a quasi (the lifetime of the energy level $^3H_5$ is only 7 ns) or true in-band pump, the train of 2-μm pulses is regular [see Fig. 4(a); the first pulse in each period is the residual pump light through the dichroic mirror, which has high reflectivity at the pump wavelengths and high transmissivity at the 2-μm band]. However, when the CW pump rises to a higher level, the feature of relaxation oscillation emerges [Fig. 4(b)], just like in the other common gain-switched lasers.

4. APPLICATIONS AND FUTURE PROSPECTS

The discovery of the in-band pump technique elimintated the obstacle between gain-switched fiber lasers and their application. In 2008, Creeden *et al.* [30] used a gain-switched Tm-doped fiber laser to pump a $ZnGeP_2$ (based on an OPO) and produced the mid-IR emission in the spectral regions of 3.4–3.9 μm and 4.1–4.7 μm. A promising conversion efficiency of >35% and 20 ns mid-IR pulse width were achieved. After that, the authors continued to improve their mid-IR OPO laser and acquired an output up to 2 W [31]. Another important application of gain-switched fiber lasers is supercontinuum generation, and it has been demonstrated in several works [29,32–34]. Larsen *et al.* [32] employed a gain-switched Yb-doped fiber laser (which is also an in-band pumped laser) to pump a photonic crystal fiber and achieved a supercontinuum spanning from 500 to 2250 nm, which is close to the non-transparent wavelength of silica. We also used a gain-switched Tm-doped fiber laser in [15] to pump a 10-m single-mode fiber, and a supercontinuum spanning over 200 nm can be observed with an average-power spectral density of $>30\ \mathrm{mW \cdot nm^{-1}}$, as shown at the bottom of Fig. 5. As a pump option for supercontinuum generation, gain-switched fiber lasers have several advantages: (1) compared to picosecond and femtosecond pulses, the nanosecond pulses generated by the gain-switched lasers can inject more energy into nonlinear fibers without facet damage, which may be the weakest aspect of fibers [5], and increase the average power of the generated supercontinuum; (2) compared to CW lasers, gain-switched pulses can stir up much more intense nonlinear effects, which will improve the supercontinuum in spectral coverage and flatness [30]; (3) compared to *Q*-switched fiber lasers, the all-fiber gain-switched fiber lasers have a simple structure without the need for alignment of free-space components.

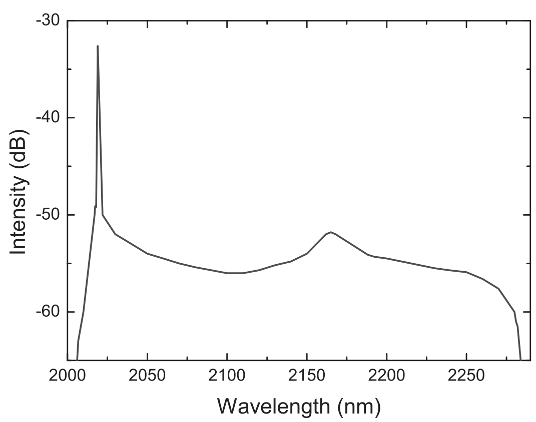

Fig. 5. Supercontinuum induced by gain-switched pulses. A 10 m single-mode fiber was spliced to the gain-switched Tm-doped fiber laser, and a supercontinuum spanning over 200 nm can be observed with an average power spectral density of $>30\ \mathrm{mW \cdot nm^{-1}}$.

Due to the laser wavelengths coinciding with the absorption peaks of water, pulsed lasers emitting from gain-switched 2-μm fiber lasers can be used to ablate soft tissues and kidney stones with thermal confinement, for little thermal damage and minimal damage to surrounding area. The applications of mid-IR pulsed fiber lasers in clinics were demonstrated successfully in the literature [35–37].

With the development of the fabrication of rare-earth-doped fibers and high-power LDs, the performance of gain-switched fiber lasers will be continuously improved in the near future. The following characteristics will still draw attention:

- Two-level structure with in-band pumping. Traditionally, the in-band pump schemes take advantage of the intrinsic characteristics of the energy level for some specific dopant fibers. Expanding of this technique to other dopant fibers that are not two-level systems may stimulate new research. The hybrid-pumped lasers mentioned in Section 3 [9,15] are successful examples. Another example is a cascade laser proposed by Li *et al.* [28], which uses a 3-μm *Q*-switched laser to induce a 2-μm gain-switched laser.
- Tm^{3+} and Ho^{3+} dopants and beyond. Due to their high quantum efficiency and intrinsic in-band pumping [38,39], Tm- and Ho-doped fiber lasers will keep their important roles in gain-switched lasers. However, the development of gain-switched mid-IR fiber are attractive, which will provide great opportunities in the exploration of new dopants, other host materials besides silica-based ones (such as fluoride and germanate), and a new in-band pump technique.
- New configuration for high pulse energy and short pulse duration. The relation between the length of the gain medium and the pulse duration requires a short gain fiber for the desired short pulse. This further requires high doping concentrations. However, too much doping concentration will cause severe heat problems and doping quenching. Exploiting new configurations, such as a ring cavity or synchronized pumping, may bring forth further development of the gain-switched fiber lasers.

5. CONCLUSIONS

In conclusion, we have reviewed briefly the development and applications of the gain-switched rare-earth-doped fiber lasers. These kinds of lasers have a very simple geometry, especially those with an all-fiber configuration, bringing increased convenience to integration and commercialization. With the development of high-power LDs, the gain-switched fiber lasers will be excellent choices for producing millijoule-energy, nanosecond-duration pulsed lasers. We have illustrated the physical mechanism of gain-switching by comparing it with that of *Q*-switching and found that the theories and formulas developed for *Q*-switching can be roughly used in the design and optimization of the gain-switched fiber lasers. By summarizing the experiments on gain-switched fiber lasers, we have explained the concentrated interest in the in-band pump scheme, especially using Tm^{3+} and Ho^{3+} dopants. With a simple numerical model, we have illustrated the advantage of an in-band pump in the gain-switched lasers. We also have discussed several efforts to improve the temporal and energy characteristics of the gain-switched fiber lasers. With regard to application, this kind of laser was used in wavelength conversion to mid-IR, supercontinuum generation, and medicine, showing excellent performance and prospects. Finally, we have given our opinions about the future characteristics of gain-switched rare-earth-doped fiber lasers.

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