Letter

A novel pulsed fiber laser: further study on the bias-pumped gain-switched fiber laser

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Abstract
The bias-pumped gain-switched fiber laser proposed by us is considered to be a novel pulsed fiber laser based on a new pulsing mechanism. With a certain signal power seeding, synchronization of the temporal evolution can be maintained between the output signal laser and the pump. The seed laser can conveniently be supplied with power by a CW pump; this is called bias-pump power. A pulsed pump is responsible for shaping the output pulse. Stable pulsed lasers with a tunable duration can be achieved under a bias pump combined with a pulsed pump. In addition, the temporal shape of the output pulses can be controlled based on this new pulsing mechanism. Compared with conventional gain-switched fiber lasers, a much simpler pulsed laser design can be provided by this novel pulsed fiber laser because there is no need to add a control unit to realize fast gain-switching.

Keywords: fiber laser, gain-switching, relaxation oscillation, bias pumping

(Some figures may appear in colour only in the online journal)

1. Introduction
The sustained interest pulsed lasers have attracted is motivated by their widespread use in micromachining applications. Q-switching and gain-switching are the two common approaches to achieve pulsed operation that realizes laser pulses with a duration of tens of nanoseconds up to several microseconds [1–3]. Compared with Q-switching, the gain-switching method offers a more compact and robust way of building a laser system. No additional active optical elements are required for modulation inside the cavity. Relying on fast modulation of the pump power, the gain-switching of a laser is considered to be the most robust and simplest way to produce nanosecond laser pulses [4]. Combined with fiber technology, gain-switched fiber lasers provide a compact and simple setup, especially in all-fiber constructions [5–13].

The temporal characteristics of gain-switched pulses, including their duration and peak power, are strongly related to the time variance of the pump power [4]. Obtaining a stable pulse that is the first spike of the relaxation oscillation requires that the pump power be switched off at the appropriate time. This is why a fast gain-switching technique is generally adopted in gain-switched fiber lasers to suppress the spikes after the initial one [14, 15]. Although there is no need to add the active optical elements that are required for modulation inside the cavity, a much more complex feedback loop is required to realize fast gain-switching.

In recent years pulsed lasers with a tunable duration have been favored in various applications [16–18]. To satisfy different applications, typically pulsed lasers with different durations and energies are required. Further, the temporal shapes of pulsed lasers are also of importance in laser applications [18]. For instance, in the case of laser micromachining, the efficiency of material removal depends on the temporal shapes and durations of pulsed lasers [18]. Consequently, pulse duration-tunable and temporal profile-controllable lasers are essential in order to ensure flexible and precise processing. However, the duration of the stable pulse output from
gain-switched fiber lasers is limited by that of the pump pulse because chaotic relaxation spikes will appear when the pump duration is long, which in some cases limits their applications. What is worse, the output pulse shape is difficult to control in current gain-switched fiber lasers.

In a previous work, we demonstrated that both long pump duration and high peak power can result in chaotic relaxation spike phenomena, and proposed a bias pumping technique to regulate the spikes in gain-switched fiber lasers [19]. However, the mechanism through which chaotic spikes are regulated by a certain pump power bias has not been explained. In addition, some new effects in bias-pumped gain-switched fiber lasers have not been investigated in detail.

In this letter, we try to explain why chaotic spikes can be suppressed with a certain pump power bias and reveal that the pulsing mechanism of this novel fiber laser is completely different from that of conventional gain-switched fiber lasers. Based on a new pulsing mechanism, we explore whether stable output pulses with a tunable duration can be generated, with the temporal profile of the output pulse being shaped as required. We also show that this novel pulsed fiber laser can provide a much simpler pulsed laser design than conventional gain-switched fiber lasers, since the feedback loop that is used in conventional gain-switched fiber lasers to achieve fast gain-switching is not necessary in this novel pulsed fiber laser.

| Table 1. Details for parameters used in the simulations [20]. |
|-------------|-------------|-------------|-------------|
| Parameter  | Value       | Parameter  | Value       |
| \(\lambda_p\) | 980 nm      | \(\sigma_{ap}\) | \(2.5 \times 10^{-24}\) m\(^2\) |
| \(\lambda_s\) | 1090 nm     | \(\alpha_s\) | \(5 \times 10^{-3}\) m\(^{-1}\) |
| \(N\) | \(2 \times 10^{26}\) m\(^{-3}\) | \(\sigma_{ps}\) | 0.39 m\(^{-1}\) |
| \(\tau\) | 1 ms        | \(\Delta\lambda_s\) | 20 nm |
| \(A\) | \(2.83 \times 10^{-11}\) m\(^2\) | \(\Gamma_1\) | 0.75 |
| \(\sigma_{es}\) | \(3.5 \times 10^{-25}\) m\(^2\) | \(\Gamma_p\) | 0.0023 |
| \(\sigma_{as}\) | \(2.0 \times 10^{-27}\) m\(^2\) | \(R_1\) | 0.99 |
| \(\sigma_{ep}\) | \(3.0 \times 10^{-24}\) m\(^2\) | \(R_2\) | 0.1 |

The rate equations (1)–(5) are given by [20]

\[
N = N_1 + N_2, \quad (1)
\]

\[
\frac{dN_2}{dt} + \frac{N_2}{\tau} = \frac{\Gamma_p\lambda_p}{hc} [\sigma_{ap}N_1 - \sigma_{ep}N_2]P_p
+ \frac{\Gamma_s\lambda_s}{hc} [\sigma_{as}N_1 - \sigma_{es}N_2](P_s + P_{sb}), \quad (2)
\]

\[
\frac{dP_p}{dz} + \frac{1}{\upsilon_p} \frac{dP_p}{dt} = \Gamma_p[\sigma_{ep}N_2 - \sigma_{ap}N_1]P_p - \alpha_sP_p, \quad (3)
\]

\[
\frac{dP_s}{dz} + \frac{1}{\upsilon_s} \frac{dP_s}{dt} = \Gamma_s[\sigma_{es}N_2 - \sigma_{as}N_1]P_s
- \alpha_sP_s + 2\sigma_{es}N_2 \frac{h}{\lambda_s^2} \Delta\lambda, \quad (4)
\]

\[
\frac{\partial P_{sb}}{\partial z} + \frac{1}{\upsilon_s} \frac{\partial P_{sb}}{\partial t} = \Gamma_s[\sigma_{es}N_2 - \sigma_{as}N_1]P_{sb}
- \alpha_sP_{sb} + 2\sigma_{es}N_2 \frac{h}{\lambda_s^2} \Delta\lambda, \quad (5)
\]

where \(N_1\), \(N_2\) and \(N\) are the lower and upper population concentrations and the total doping concentration, respectively. \(h\), \(\tau\) and \(c\) are the Planck constant, fluorescence lifetime and the speed of light in a vacuum, respectively. \(\Gamma_1\) and \(\lambda_s\) are the overlap factor between the signal and the doped fiber area and the signal free-space wavelength, respectively. \(\Gamma_p\) and \(\lambda_p\) are the overlap factor between the pump and the doped fiber area and the pump free-space wavelength, respectively. \(A\) is the core area of the fiber. \(\sigma_{es}\) and \(\sigma_{as}\) are the emission and absorption cross-sections of the signal power, respectively. \(\sigma_{ep}\) and \(\sigma_{ap}\) are the emission and absorption cross-sections of the pump power, respectively. The attenuation of the signal and pump powers are represented by \(\alpha_s\) and \(\alpha_p\), respectively. \(P_{sb}\), \(P_s\) and \(P_p\) are the backward signal power, the forward signal power and the pump power, respectively. \(\upsilon_s\) and \(\upsilon_p\) are the group velocities of the signal laser and the pump propagating in the fiber, respectively. \(\Delta\lambda\) is the bandwidth of the amplified spontaneous emission (ASE).

The rate equations (1)–(5) are governed by the boundary conditions physically representing the feedback provided by the reflectors at either end. The typical boundary conditions for equations (1)–(5) are given by

\[
P_p(z = 0, t) = W_0, \quad (6)
\]

\[
P_s(z = 0, t) = R_1P_{sb}(z = 0, t), \quad (7)
\]

\[
P_{sb}(z = L, t) = R_2P_s(z = L, t), \quad (8)
\]

\[
P_{out}(z = L, t) = (1 - R_2)P_s(z = L, t), \quad (9)
\]

where \(R_1\) and \(R_2\) are the reflectivities of reflector 1 and reflector 2, respectively, and \(P_{out}\) is the output signal power. The details for the parameters used in the simulation are summarized in table 1.

Figure 1 is the simulation result based on rate equations (1)–(5) and the boundary conditions (equations (6)–(9)). When the continuous wave (CW) pumping power is...
above the threshold, relaxation oscillation will inevitably occur before the output laser reaches a steady state, as seen in figure 1(a). The relaxation oscillation consists of several spikes. With the power starting from zero, the first spike has the highest peak power and the narrowest duration. As can be seen from the inset of figure 1(a), the laser power after the first spike does not decrease to zero, and then the second spike appears. This means that the second spike is seeded with a certain amount of laser power (about 0.5 W). The seeded power (about 5.2 W) of the third spike is higher than that of the second one, as shown in figure 1(b). The laser power at the interval of two adjacent spikes, which serves as a seed for the later one, becomes higher and higher with time. Seeded with higher power, the duration (amplitude) of the spike is wider (lower) than that of the previous one. Therefore, it is natural to ask whether it is the increase of the seed power that results in the decrement of the amplitude and the broadening of the duration of the following spike. In the following, we will study the effects caused by the seeded laser based on the parameters in table 1.

With a certain power ($W_s$) of the signal laser continuously seeding into the fiber from the same side as the pump injection (at $z = 0$), the boundary condition of the forward signal power is changed to $P_{sf}(z = 0, t) = R_1P_{sb}(z = 0, t) + W_s$. The simulation results for the seeded fiber laser are shown in figure 2.

Seeded with different signal powers, the temporal characteristics of the outputs from the CW pumped fiber laser are depicted in figure 2. Compared with figure 1(a), the amplitude of the relaxation oscillation spikes is greatly reduced with signal laser seeding, as shown in figure 2. Both the amplitude and the number of relaxation spikes decrease gradually with the increase of the seeded power. That is to say, the higher the seeded power, the shorter the duration of the relaxation oscillation becomes, and the earlier the CW steady state of output is reached. Consequently, we have reason to believe that the relaxation oscillation can be completely eliminated when the seeded power increases to a certain value. If the fiber laser is continuously seeded with a signal power of 10 W, the output laser quickly (after 0.5 $\mu$s) reaches a CW state without experiencing relaxation oscillation, as shown in the green line of figure 2. Therefore, we can safely conclude that the seeded power of the signal can mitigate the relaxation oscillation of the output laser.

In our previous work, we demonstrated that the chaotic spikes of gain-switched fiber lasers can be eliminated with a bias-pumping technique [19]. In fact, the bias-pumped power is responsible for generating the signal laser at the interval of two adjacent pulses. It is the CW signal laser, which serves as a seed for the next pulse, produced by the bias-pump power, that in reality regulates the chaotic spikes of the outputs in bias-pumped gain-switched fiber lasers. Thus, adopting bias-pumping is a simple approach to implement laser seeding. Obviously, the pulsing mechanism of the bias-pumped gain-switched fiber laser is not based on relaxation oscillation. In this sense, it is a novel pulsed fiber laser based on a new pulsing mechanism, which deserves to be further investigated.
3. Pulse-shaping in the bias-pumped gain-switched fiber laser

Figure 3 is a schematic of the bias-pumped gain-switched fiber laser. The linear cavity consists of a Yb-doped double-cladding fiber with a length of 1 m and fiber Bragg grating pairs. A pulsed pump and a CW bias pump constitute the pump source of the bias-pumped gain-switched fiber laser. Both the pulsed and CW bias pump source consist of several high-power laser diodes that are readily available for the Yb-doped fiber. Using the main parameters in table 1, we simulate how stable pulses are produced in this novel fiber laser.

Instead of seeding the signal laser at one side of the fiber continuously, the seeded signal laser can be obtained more easily by switching on the bias pump first. It is just a CW pumped fiber laser, with only bias-pump operation. After experiencing relaxation oscillation, the output laser reaches a CW steady state under a bias-pumped power of 50 W, as seen in figure 4(a). Then the signal laser in the CW state serves as a seed for the signal pulse to be generated and a pulsed pump with a peak power of 1000 W and a Gaussian profile is switched on. The simulation results are shown in figure 4(a). Stable signal pulses are produced and their durations are almost the same as those of the pump pulses depicted.
of the output pulse and $N_2(z = 0, t)$ (at the position of $z = 0$) when the profile of pump pulse is flat-topped with smoothly rising and falling edges.

in figure 4(a). Even if the duration of the Gaussian pump pulse increases to 2 $\mu$s, a stable pulse can also be realized without relaxation spikes appearing.

The simulation results for the case where the profile of the pump pulse is changed from a Gaussian profile to a six-order super-Gaussian profile are shown in figure 4(b), with the other parameters remaining the same as those in figure 4(a). In the six-order super-Gaussian profile case, spikes in the front edge of the output pulse cannot be eliminated completely with a pulsed pump duration of 0.4 $\mu$s. When the duration of the six-order super-Gaussian profile is broader than 1.2 $\mu$s, the chaotic spikes disappear and stable output pulses are achieved. Both shorter pulse duration and a higher order super-Gaussian profile mean faster power changes at the edge of the pump pulse, which tends to result in relaxation oscillation.

The simulation results in figures 4(a) and (b) clearly show that the output pulses can keep the same durations as those of the pump pulses. Consequently, the output pulse duration can be tuned by managing the pump pulse duration. Stable output pulse trains with different durations are produced under a sequence of pump pulses with different durations, and the results are shown in figure 4(c) (with a Gaussian pump profile) and figure 4(d) (with a six-order super-Gaussian profile). Between two adjacent output pulses, the emission laser is nearly in a CW state with nonzero power, which serves as a seed for the next pulse to suppress the chaotic relaxation spikes. In addition, the profiles of the output pulses are almost identical to those of the pump pulses adopting 5% bias pumping, as shown in figure 4. This means that the profile of the output pulse can be shaped by controlling the pump pulse profile. Therefore, we obtain a method to control the temporal shape of signal pulses in fiber lasers. For example, laser pulses with a flat-top profile can be obtained by adopting the bias-pumping technique and modulating the pump profile as a flat-topped shape with smoothly rising and falling edges, as illustrated in figure 5. In practice, the time variation of the pump power is modulated easily as a flat-topped profile with smooth edges that can be approximated with a super-Gaussian profile.

The temporal evolution of upper level population density $N_2(z = 0, t)$ at the position of $z = 0$ is also simulated. With a seeded laser suppressing the relaxation spikes, there is no population oscillation across the output pulses, as shown in figures 4(c), (d) and 5. However, slight population oscillation occurs at both edges of the output pulses when the pump pulse changes quickly, as seen the blue lines in figures 4(d) and 5. The temporal characteristics of $N_2(z = 0, t)$ further indicate that the mechanism of pulse formation in this novel pulsed fiber laser is not based on relaxation oscillation. The peak power of the flat-topped pulse in figure 5 lasts about 3 $\mu$s, which is actually in a CW steady state. Synchronization of the temporal evolution between the output signal pulse and the pump pulse is realized with signal laser seeding, which is the mechanism of pulse shaping in this novel pulsed fiber laser.

Based on this new pulsing mechanism, the bias-pumped gain-switched fiber laser has the potential to generate stable pulses with tunable durations and controllable pulse shapes. Because the temporal evolution of the output pulse is synchronous with that of the pump pulse, the duration and temporal profile of the output pulse are almost the same as those of the pump pulse. Since no relaxation spikes occur under long pump durations, we do not have to rely on a fast gain-switching technique to switch the pump off/on rapidly. Therefore, the control unit that monitors the laser output and controls the pumping diodes in conventional gain-switched fiber lasers can be left out in this novel pulsed fiber laser.

4. Conclusion

We consider a bias-pumped gain-switched fiber laser that is a novel pulsed fiber laser based on a new pulsing mechanism. The key factor for this novel pulsed fiber laser is the synchronization of temporal evolution between the output signal laser and the pump, which requires signal laser seeding with a certain power. The bias-pumping technique proposed by us is a convenient way to supply a seed laser that can suppress relaxation oscillation. Stable output pulses with tunable durations can be obtained under a CW bias pump combined with a pulsed pump. The CW bias-pump power is responsible for supplying the seed laser and the pulsed pump is responsible for shaping the output pulse. With a certain signal power seeding, the output pulse can maintain almost the same duration and temporal profile as those of the pump pulse, as long as the pump profile is smooth. Thus, the temporal characteristics of output pulse, including duration and pulse shape, can be controlled by management of the pump pulse. In addition, the control unit used to realize fast gain-switching in conventional gain-switched fiber laser can be left out in this novel pulsed fiber laser, which greatly simplifies the pulsed laser design. Based on the new pulsing mechanism and excellent output pulse characteristics, this kind of novel pulsed fiber laser may open up novel industrial and scientific applications.
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