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Saturable-Absorber Q-Switched All-Fiber Ring Lasers

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1. Introduction

A Q-switched fiber laser with a small core diameter could directly provide a high intensity-density output of 1-100 MW/cm^2 without external focusing components. Such a high intensity density is quite useful for micromachining, nonlinear optics studies and biomedical applications. Like most of the conventional bulk Q-switched lasers, Q-switched fiber lasers have been realized using similar active [1, 2] and passive [3-5] bulk Q-switches. These fiber lasers contain free-space sections in the resonators, and require sophisticated techniques of alignment for pump coupling and in-and-out light coupling between fibers, Q-switches and mirrors.

Lately an increasing attention has been drawn upon the all-fiber Q-switched lasers that require no alignments and have inherently low cavity losses. An all-fiber laser is generally a single-mode system pumped with a single-mode laser diode of hundreds of milliwatts. The laser is composed of commercial fiber components as WDMs, FBGs, fibers and fiber-pigtailed components of low insertion losses. Although an all-fiber system has limited CW output power for the small core diameters and the low-power LD pump, pulses with comparably high intensity densities can still be achieved in an all-fiber Q-switched laser with a relatively low price.

In this paper, we propose a simple scheme of an all-fiber SAQS ring laser and establish the location-dependent rate equations to keep track of the non-uniform distributions of the resonant photons, the gain population inversion in the gain fiber N_g and the absorption population in the SAQS fiber, N_a. The design was numerically and experimentally demonstrated using single-mode Er^{3+}- doped fiber at the emission wavelength of 1550 nm. More than 90% extraction efficiency of N_g by a Q-switched pulse was obtained. It is important to note that the proposed design is applicable for self Q-switching performances of all the 3-level laser materials that can also serve as 2-level saturable absorbers at the emission wavelength.

2. Modeling and Simulation

Figure 1 shows the schematic design of an all-fiber SAQS ring laser.

It is reasonable to expect that the photon density in the absorber fiber should be on average twice (or more than twice) that in the gain fiber. The more intense photon density would result in a fast bleaching of the absorber, and then lead to a passive Q-switching performance.

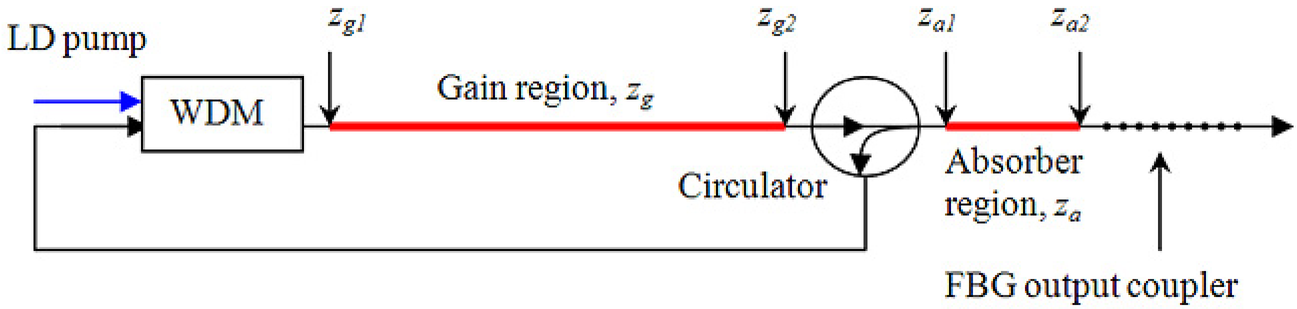

Fig. 1. Schematic design of a passively Q-switched all-fiber ring laser

In simulation, time is scaled by $t=k\times t_r$, where t_r is the roundtrip transit time and k is a positive integer. In every time slice, $N_g(z)$ and $N_a(z)$ are solved iteratively by the rate equations:

$$N_a(z_a,k)-N_a(z_a,k-1)=-p_aK_aN_a(z_a,k-1)n_a(z_a,k-1)\cdot t_r, \quad (1)$$

$$N_g(z_g,k)-N_g(z_g,k-1)=-p_gK_gN_g(z_g,k-1)n_g(z_g,k-1)\cdot t_r. \quad (2)$$

The pump rate and the population relaxation are negligible in the Q-switching duration and ignored in the equations. In every time step, once $N_g(z,k)$ and $N_a(z,k)$ are obtained, $n(z,k)$ is calculated accordingly along the propagation direction by

$$\begin{aligned}
n_g(z_g,k) &= n_{ar}(z_{a1},k-1)e^{-\alpha_2}\exp\left(\frac{\sigma_g}{A_g}\int_{z_{g1}}^{z_g}N_g(z,k)dz\right) \textit{ in the gain region,}\\
n_{ai}(z_a,k) &= n_g(z_{g2},k)e^{-\alpha_1}\exp\left(-\frac{\sigma_a}{A_a}\int_{z_{a1}}^{z_a}N_a(z,k)dz\right) \textit{ from } z_{a1} \textit{ to } z_{a2},\\
n_{ar}(z_a,k) &= n_{ai}(z_{a2},k)e^{-\alpha_f}\exp\left(\frac{\sigma_a}{A_a}\int_{z_{a2}}^{z_a}N_a(z,k)dz\right) \textit{ from } z_{a2} \textit{ to } z_{a1},\\
n_a(z_a,k) &= n_{ai}(z_a,k)+n_{ar}(z_a,k) \textit{ in the absorber region,}
\end{aligned} \quad (3)$$

The simulation starts from the threshold condition when the gain is equal to the total loss. Before lasing ($t<0$), the pump intensity $I_p(z_g)$ and the corresponding $N_g(z_g)$ can be numerically solved for the initial condition:

$$\frac{\sigma_g}{A_g}\int_{z_{g1}}^{z_{g2}}N_{gth}(z,0)dz=\left(-\alpha_1-\alpha_f-\alpha_2-2N_T\sigma_a l_a\right), \quad (4)$$

The other initial variables and parameters are $n_g(z_{g1},0)=1\times10^2$, $A=1.26\times10^{-7}$ cm^2, t_r=18 ns, $\sigma_g=\sigma_a=5\times10^{-21}$ cm^2 and $N_T=1.38\times10^{19}$ cm^{-3}. The parameters are based on the characteristics of the erbium fiber employed in the experiment. The simulation result is shown in Fig. 2. A passively Q-switched pulse has peak power of 1.72 W and pulse duration of 198 ns.

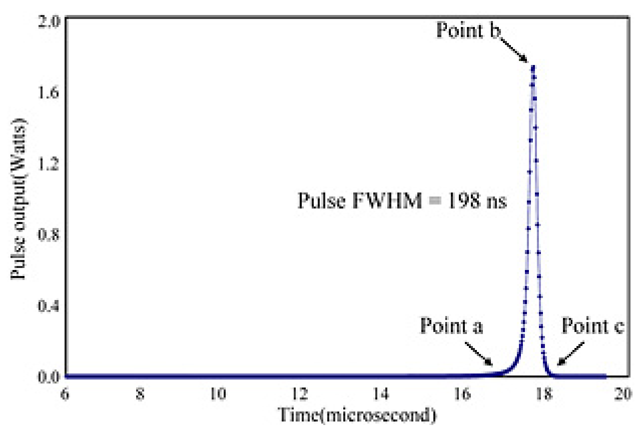

Fig. 2. Pulse simulation of a passively Q-switched all-fiber ring laser.

Figure 3 shows $N_g(z_g)$ and $N_a(z_a)$ at the moments t_a, t_b and t_c, normalized by the initial $N_g(z_{g1},0)$ and $N_a(z_{a2},0)$. It is clear that the SAQS fiber is saturated faster than the gain fiber, and well bleached at the end of the pulse.

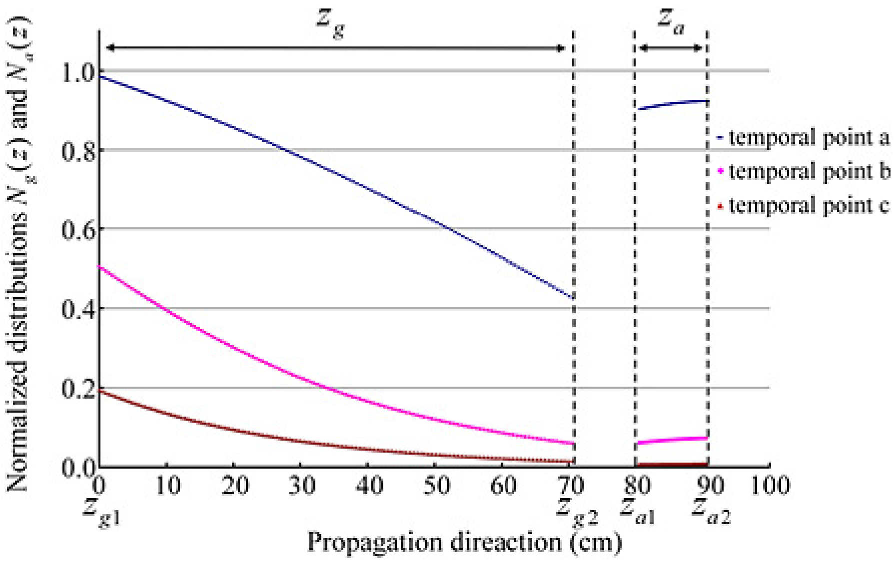

Fig. 3. Saturations of N_g(z) and N_a(z) by the pulse, observed at the beginning, the top and the end of the pulse. The time points are marked with a, b, c in Fig.2.

3. Experiment

The experiment was arranged as depicted in Fig. 1. The erbium fiber used for the gain and the SAQS in the experiment had an absorption loss of 30 dB/m at 1550 nm, and a core diameter of 4 μm. The length of the absorber was 10 cm and that of the gain fiber was 70 cm. The reflectivity of the FBG output coupler was about 90% at 1550nm with a bandwidth less than 0.3 nm. The total roundtrip length of the ring resonator was about 360 cm. All the applied characteristics were similar to the parameters used in the previous simulation. The laser output was detected by a 175-ps fast EOT ET-3000 InGaAs photodetector.

Steady sequentially Q-switched pulses were obtained, as shown in Fig. 4. The modulation rate was set to be 25 Hz. Each pulse appeared about 12 ms after the rising edge of the pump. The pulse had pulse energy of 0.37 μJ and pulse FWHM of 218 ns. The peak pulse power of 1.69 W was achieved, in very good agreement with the simulation result.

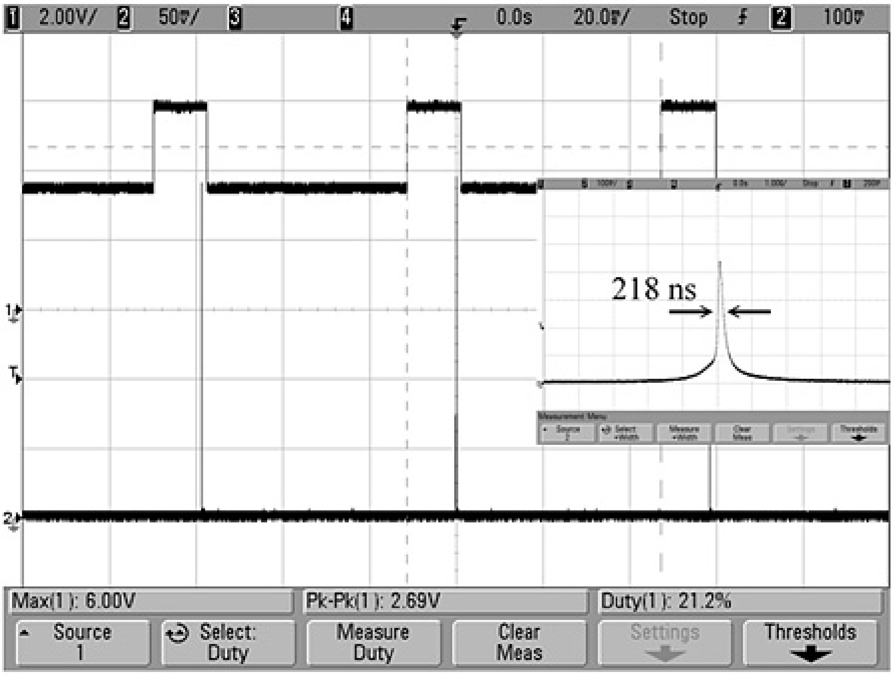

Fig. 4. A steady output of sequentially SAQSed pulses. The square waveform was the driving current applied on the 980-nm pump laser diode. The measured pulse energy was 0.37 μJ, and the pulse duration was 218 ns.

4. Conclusion

We have proposed a simple design for all-fiber saturable absorber Q-switched lasers, and numerically and experimentally demonstrated the high efficiency of Q-switching performance using single-mode erbium-doped fibers. A set of location-dependent rate equations was established for modeling the Q-switching dynamics and the time variations of $n(z)$, $N_g(z)$, and $N_a(z)$. In the experiment, peak pulse power of 1.69 W with pulse FWHM of 218 ns was achieved with 7-mW pump power of a 980-nm LD. The experimental data was in solid agreement with the simulation result. The proposed laser scheme is compact, economic, efficient and applicable for various laser materials.

References

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