DOI 10.1007/s10946-018-9759-4
Journal of Russian Laser Research, Volume 39, Number 6, November, 2018

A NOVEL 1,066 nm $\mathrm{Nd{:}Gd_{0.69}Y_{0.3}NbO_4}$ PASSIVELY Q-SWITCHED PULSE-BURST LASER

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Abstract

We demonstrate for the first time a $\mathrm{Cr^{4+}}$:YAG passively Q-switched 1066 nm pulse-burst laser under 879 nm direct pump with a novel $\mathrm{Nd{:}Gd_{0.69}Y_{0.3}NbO_4}$ crystal. The output laser characteristics with different pump repetition rates and different $\mathrm{Cr^{4+}}$:YAG initial transmission are studied. Without the $\mathrm{Cr^{4+}}$:YAG, we obtain a maximum output energy of 2.55 mJ at an absorbed pump energy of 5.79 mJ with the highest 48% slope efficiency. The pulse-burst laser contains a maximum of 7 pulses for a $\mathrm{Cr^{4+}}$:YAG initial transmission of 55% and a pump repetition rate of 1 kHz. The single-pulse energy and narrowest pulse width reach 160 μJ and 5.5 ns at 38.2 kHz, with a peak power of 32 kW.

Keywords: $\mathrm{Nd{:}Gd_{0.69}Y_{0.3}NbO_4}$, burst mode, passive Q-switching, direct pump.

1. Introduction

Diode-pumped high-repetition-rate lasers with short pulse width and high peak power have been used in many areas such as laser processing, laser-induced plasma ignition, laser lidar, and laser ranging [1–3]. Passive Q-switching has the advantages of compactness, low cost, and simplicity in set-up, and $\mathrm{Cr^{4+}}$:YAG is the most used passive Q-switch due to its large absorption cross sections, excellent thermal characters, and low saturated intensities [4–6]. In 2016, a new mixed laser crystal $\mathrm{Nd{:}Gd_{0.69}Y_{0.3}NbO_4}$ with high quality was grown successfully by the Czochralski method [7]. Compared with the commonly employed neodymium ion-hosted crystals, such as Nd:YAG whose absorption bandwidth at 808 nm absorption line is about 1.5 nm, the absorption bandwidth at 808 nm for b-cut $\mathrm{Nd{:}Gd_{0.69}Y_{0.3}NbO_4}$ is about 14 nm [8].

Manuscript submitted by the authors in English on August 9, 2018.

Therefore, this new mixed crystal has the potential to reduce the demands of pumping light bandwidth. In addition, the Nd:GdYNbO$_4$ upper-level lifetime (156 μs) [7] is smaller than that of Nd:YAG (240 μs), which has advantage in producing high-repetition-rate lasers.

In 2016, Shoujun Ding et al. demonstrated the CW Nd:GdYNbO$_4$ laser operation of 808 nm pumping for the first time. A maximum output power of 0.98 W was obtained with a 31.3% optical-to-optical conversion efficiency and a 30.4% slope efficiency [8]. In 2017, Yufei Ma et al. demonstrated the CW and passively Q-switched operation of an 808 nm pumped Nd:GdYNbO$_4$ laser. A maximum output power of 2.13 W was obtained with a 10.5 W absorbed pump power. Laser pulses with a single-pulse energy of 26.7 μJ and a shortest pulse width of 7.2 ns were obtained at a repetition rate of 19 kHz [9]. Instead of the continuous pulse mode, the pulse-burst mode can realize both high repetition rate and high pulse energy simultaneously in a short period [10]. For the Nd^{3+} ion, direct pumping to the upper laser level ^{4}F$_{3/2}$ has advantages of high efficiency and low waste heat [11–13].

In this paper, we demonstrate a miniaturized 879 nm LD directly-pumped passively Q-switched pulse burst 1,066 nm laser with a novel Nd:Gd$_{0.69}$Y$_{0.3}$NbO$_4$ mixed crystal for the first time. We study and optimize the output laser performances of different pulse-burst repetition rates and different output coupler transmittances. The pulsed Nd:GdYNbO$_4$ laser characteristics are investigated with different initial transmissions when the Cr^{4+}:YAG crystal is used as saturated absorber.

2. Experimental Setup

The schematic diagram of the passively Q-switched Nd:GdYNbO$_4$ pulse-burst laser is shown in Fig. 1. A pulsed 879 nm LD serves as the pump source with a repetition rate of 1 or 2 kHz, and the pump duration is about 200 μs. The pump light is coupled into a fiber with a diameter of 400 μm and a N.A. of 0.22. A volume Bragg grating is used to stabilize the LD output wavelength at 879 nm. A coupling optics system composed with L$_1$ ($f_{\rm L1}$ = 32.1 mm) and L$_2$ ($f_{\rm L2}$ = 34.2 mm) is used to reimage the pump light into the laser crystal. The geometrical laser cavity with the plane mirror M$_1$ and M$_2$ is about 50 mm. The plane M$_1$ provides antireflection at 879 nm and high reflectivity at 1.06 μm. The output coupler M$_2$ has different transmittances of 20%, 25%, and 30% at 1.06 μm. A b-cut Nd:GdYNbO$_4$ mixed crystal with the 1.0 at.% Nd^{3+} concentration is used as the laser gain medium. The dimension of the crystal is 2×2×4 mm. Both faces of the laser load are coated with high transmission at 879 nm and 1.06 μm. The crystal is wrapped with indium foil and placed into a copper water-cooling microchannel sink. The Cr^{4+}:YAG crystal is used as the saturated absorber, and the initial transmission is 55% or 85% at 1.06 μm.

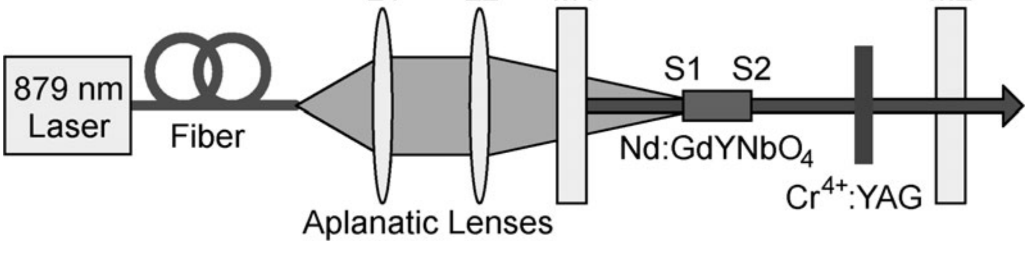

Fig. 1. Experimental setup of a Nd:GdYNbO$_4$ laser.

3. Results and Discussions

First, we investigated the pulse-burst laser performance without the Cr^{4+}:YAG. The results are shown in Fig. 2. The laser output characteristics with different output coupler transmissions of 20%, 25%, and 30% were studied at pump repetition rates of 1 and 2 kHz. The output energy increased with the absorbed pump energy. When the pump repetition rate was 1 kHz, at an absorbed pump energy of 5.79 mJ, the maximum output energy was 2.47, 2.55, and 2.36 mJ, respectively, for the M_2 with transmissions of 20%, 25%, and 30%. For the 25% output coupler transmission, we obtained the highest slope efficiency of 48.0% with this new mixed (to our knowledge) crystal. The threshold absorbed pump energy was about 0.2 mJ. For the 2 kHz pump repetition rate, we obtained the maximum output energies of 1.67 ($T = 20\%$), 1.74 ($T = 25\%$), and 1.54 mJ ($T = 30\%$) at a 5.37 mJ absorbed pump energy.

For different pump repetition rates, the output coupler with a transmission of 25% appears to be the best available choice. In the following passive *Q*-switched operation, the M_2 mirror with $T = 25\%$ at 1,066 nm was chosen as the output coupler. In Fig. 2, we see that the output energy was lower at 2 kHz and, in the high-absorbed pump energy range, the saturated phenomenon was more significant. This phenomenon can be explained by the significant thermal effect of higher pump repetition rate. At the output energy of 2.55 mJ, we measure the laser beam diameters by the knife-edge method. The M^2 was estimated to be 2.55. The output beam profile was measured by a beam analyzer (LBA-712PC-D, Spiricon Inc.). As shown in Fig. 3, the laser distribution had a good symmetry.

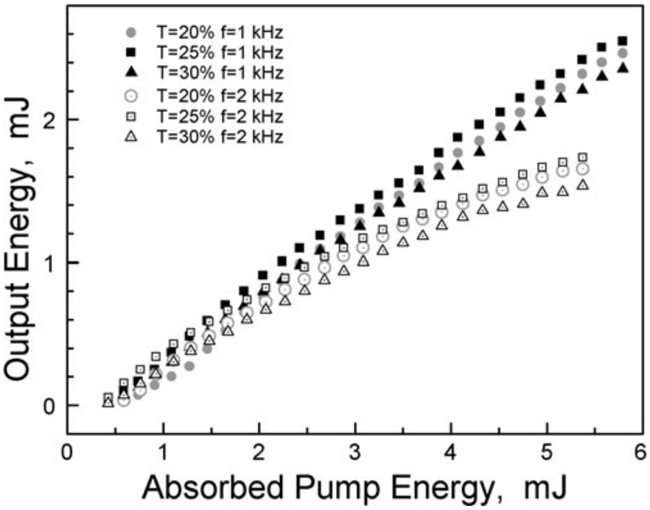

Fig. 2. The output energy without *Q*-switching as a function of the absorbed pump energy.

In the passively *Q*-switched pulse-burst operation, the Cr^{4+}:YAG crystals with initial transmissions of $T_0 = 55\%$ and $T_0 = 85\%$ were tested in order to

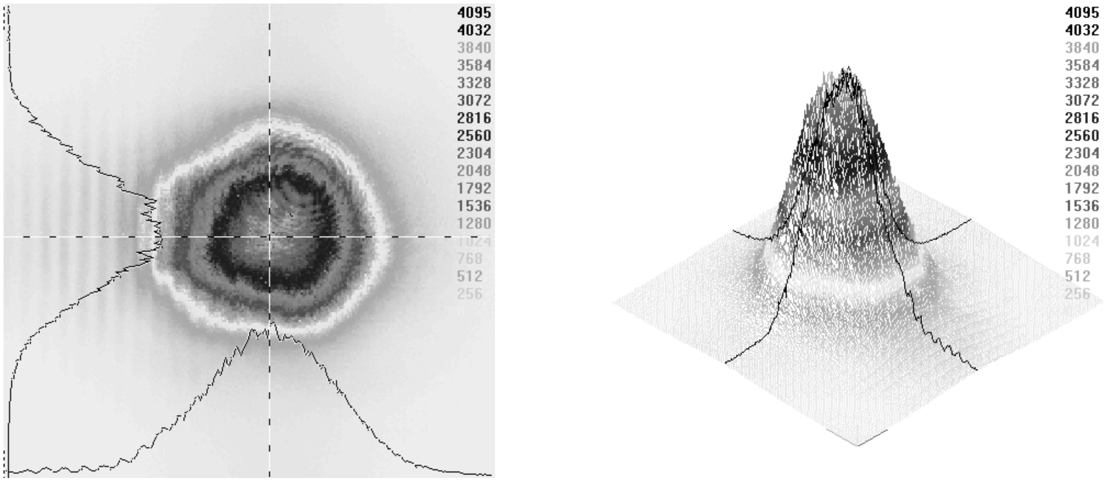

Fig. 3. Beam profile of a Nd:GdYNbO$_4$ laser with the 2.55 mJ output.

investigate the passively Q-switched laser properties. Figure 4 shows the output energy as a function of absorbed pump energy with the Cr^{4+}:YAG 55% initial transmission. We can see that the output energy remained constant until the following pulse is generated with the increased absorbed pump energy. When there was more than one pulse produced in one pumping period, the pulses demonstrate the pulse-burst operation. The maximum 7 and 5 pulses are generated during one pulse burst for pump repetition rates of 1 and 2 kHz, respectively. Highest pulse burst energies of 1.1 and 0.75 mJ were obtained at an absorbed pump energy of 5.79 mJ for pump repetition rates of 1 and 2 kHz, respectively. The corresponding single pulse energies were 0.16 and 0.14 mJ. The lost output energy at a higher pump repetition rate can be explained by the more substantial thermal effect.

In Fig. 5, we show the laser output characteristics when the Cr^{4+}:YAG crystal initial transmission was changed to 85%. One can observe that the pulse burst energy increases with increase in the absorbed pump energy. Due to the higher initial transmission, the pulse burst contained 3 pulses at the threshold absorbed pump energy. The maximum of 21 and 17 pulses were obtained during one burst at pump repetition rates of 1 and 2 kHz, respectively. Corresponding pulse burst energies of 1.62 and 1.13 mJ were obtained at absorbed pump energies of 5.79 and 5.37 mJ, respectively. The single pulse energies were 77 and 66 μJ. Similar properties were exhibited by the passively Q-switched laser with the 55% initial transmission, but the single pulse energy became lower and the pulse number during one burst was caused more by the higher Cr^{4+}:YAG initial transmission.

According to the theory of passively Q-switched lasers, the pulse repetition frequency shows a linear dependence on the pump power. The repetition rate of laser pulses in the pulse burst with different Cr^{4+}:YAG initial transmissions is shown in Figs. 6 and 7. For the 55% initial transmission, the passively Q-switched repetition frequency increased from 15.8 kHz in the 2-pulse burst to 38.2 kHz in the 7-pulse burst. For the 85% initial transmission, the repetition rate increased from 26.9 kHz in the 3-pulse burst to 127.5 kHz in the 21-pulse burst. The temporal pulse trains at 38.2 and 127.5 kHz are shown in Fig. 8. At a low repetition frequency, the oscilloscope trace demonstrates fair good amplitude and temporal stability, but at a higher repetition rate, there are visible fluctuations caused by the significant thermal effect at high absorbed pump energy.

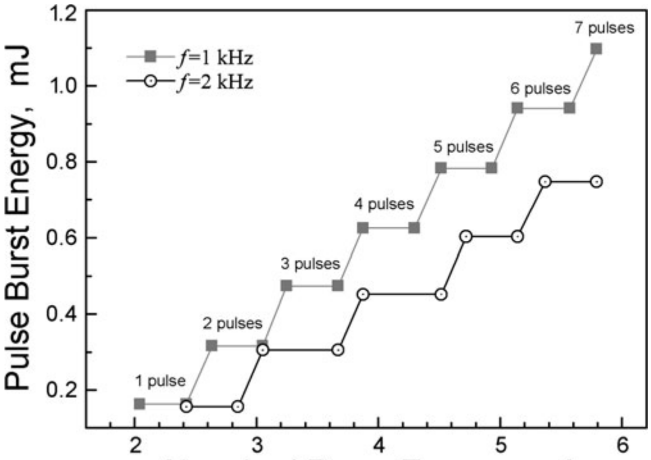

Fig. 4. The output energy of the Nd:$GdYNbO_4$ passively Q-switched laser with the Cr^{4+}:YAG 55% initial transmission.

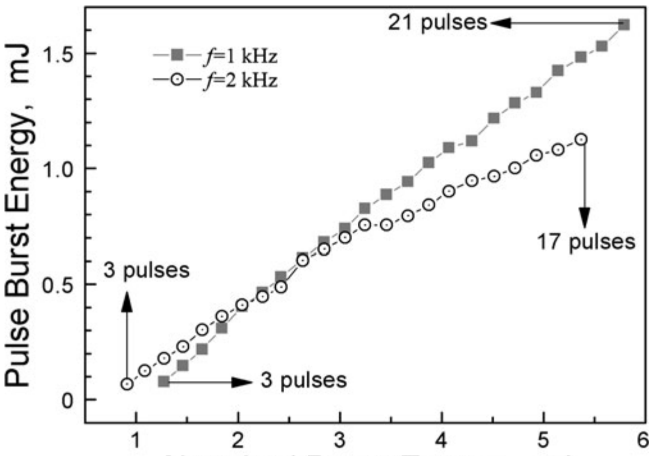

Fig. 5. The output energy of the Nd:$GdYNbO_4$ passively Q-switched laser with the Cr^{4+}:YAG 85% initial transmission.

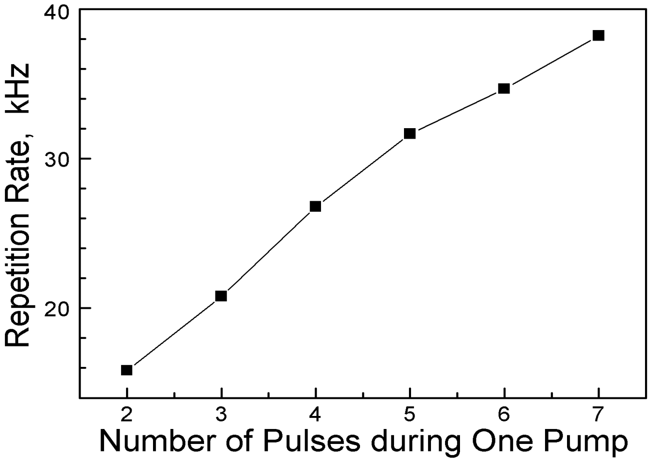

Fig. 6. The repetition rate as a function of the pulse number during one pump pulse with the Cr^{4+}:YAG 55% initial transmission.

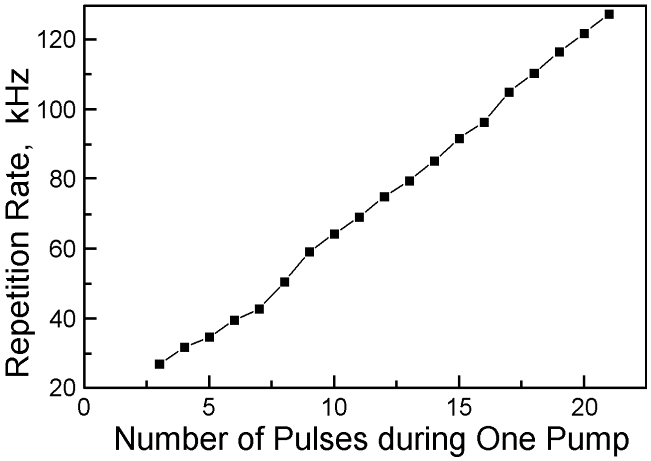

Fig. 7. The repetition rate as a function of the pulse number during one pump pulse with the Cr^{4+}:YAG 55% initial transmission.

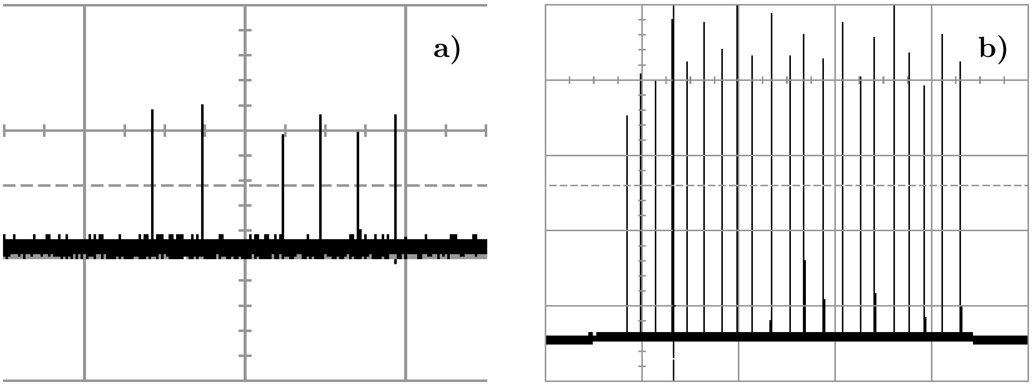

Fig. 8. Temporal oscilloscope traces of the pulse burst laser for 7 pulses (a) and 21 pulses (b).

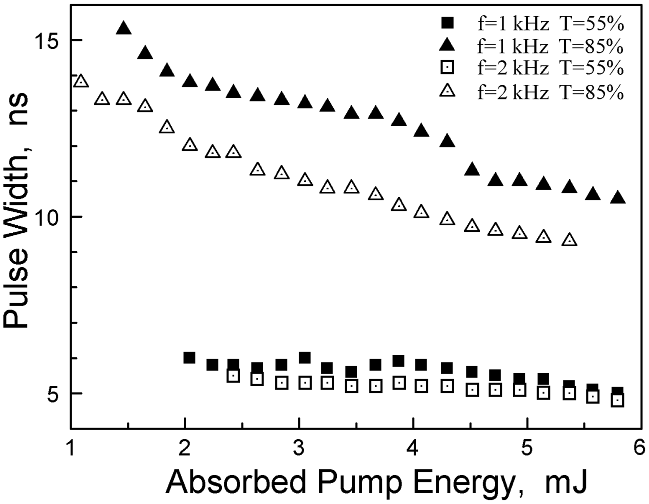

Fig. 9. Pulse width in *Q*-switched pulse-burst laser as a function of absorbed pump energy.

In Fig. 9, we show the pulse width as a function of absorbed pump energy with different Cr^{4+}:YAG initial transmissions and different pump repetition rate. We can see that the pulse width decreases slightly with increased absorbed pump energy. The pulse width of the 85% initial transmission is higher than that of the 55% initial transmission. When the pump repetition rate changes from 1 to 2 kHz, the pulse width also shows a slight decrease. From our point of view, this decrease is caused by a higher pump at a higher pump repetition rate.

For the Cr^{4+}:YAG with the 85% initial transmission, the narrowest pulse widths were 10.5 and 9.3 ns at the 1 and 2 kHz pump repetition rate, respectively. The highest peak powers were estimated

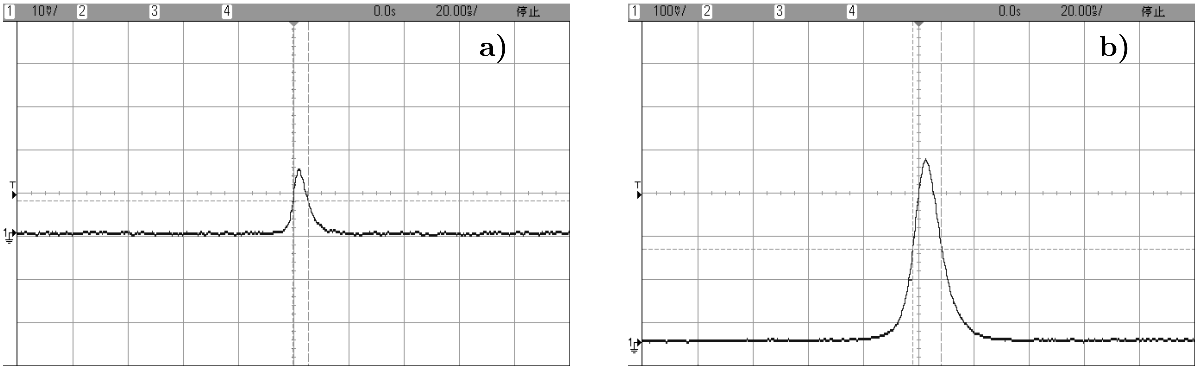

Fig. 10. Temporal pulse profile of 5.5 ns (a) and 10.5 ns (b).

to be 7.39 and 7.17 kW. For the Cr^{4+}:YAG with the 55% initial transmission, the narrowest pulse width were 5 and 4.8 ns at pump repetition rates of 1 and 2 kHz. The corresponding peak powers were 32 and 29.16 kW, respectively. Figure 10 demonstrates temporal pulse profiles of 5.5 and 10.5 ns.

4. Conclusions

In conclusion, we demonstrated a miniaturized Cr^{4+}:YAG passively Q-switched pulse-burst laser with a novel Nd:$Gd_{0.69}Y_{0.3}NbO_4$ mixed crystal under the 879 nm direct pump. Without the Cr^{4+}:YAG saturated absorber, we investigated the output characteristics of the pulse burst laser with different pump repetition rates and different output mirror transmissions. A maximum output energy of 2.55 mJ was obtained at an absorbed pump energy of 5.79 mJ with a 48% slope efficiency. At the passively Q-switched pulse-burst laser operation, we studied the output characteristics with Cr^{4+}:YAG initial transmissions of 55% and 85%. When the Cr^{4+}:YAG with the 55% initial transmission was used, a pulse burst with 7 and 5 pulses was obtained with a pulse burst energy of 1.097 and 0.747 mJ at an absorbed pump energy of 5.79 mJ and pump repetition rates of 1 and 2 kHz, respectively. The corresponding narrowest widths and peak powers were 5.5 and 4.8 ns and 32 and 29.16 kW, respectively.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NSFC) under Grants Nos. 61605032, 61505042, and 61505041, Shenzhen Science and Technology Program under Grant No. JSGG20170414141239041, General Financial Grants from the China Postdoctoral Science Foundation Nos. 2015M80263, 2014M560262, and 2013M531040, Special Financial Grants from the China Postdoctoral Science Foundation Nos. 2014T70336 and 2015T80350, Postdoctoral Fellowship in Heilongjiang Province under Grants Nos. LBHZ13081 and LBH-Z14074, and the Fundamental Research Funds for Central Universities under Grants No. HIT. NSRIF. 2017018 and 2015044.

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