Vol 12 No 11, November 2003
1009-1963/2003/12(11)/1246-05
Chinese Physics
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The mechanism research of the $Cr^{4+}Nd^{3+}$:YAG laser*

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(Received 14 March 2003; revised manuscript received 2 June 2003)

The 946nm diode-pump microchip self-Q-switched laser of a chromium and neodymium codoped yttrium aluminum garnet crystal material ($Cr^{4+}Nd^{3+}$:YAG) is studied, especially about its physical mechanism of operation. The $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition of Nd^{3+} ion is beneficial to achieving laser oscillation in a quasi-three-level system based on coating the cavity mirrors of the microchip with films that suppress the 1064nm operation and enhance the 946nm laser. The Cr^{4+} ion is a saturable absorber. The initial loss N_{t1} is high, which acts as the threshold for laser oscillation. The stable loss N_{t2} is low because the Cr^{4+} ion is acceleratively bleached by the fast enhancement of the oscillating laser. The high N_{t1}, small N_{t2} and fast progresses permit the oscillating laser of the $Cr^{4+}Nd^{3+}$:YAG to have a good self-Q-switched property whose full width at half maximum is about 4.2ns. Its highest laser power is about 5.7mW. Its peak power is about 150W. Its good fundamental transverse TEM_{00} mode results from the absorption bleaching established by both the pump and oscillating lasers, which suppress other transverse mode and allow the oscillation only in the fundamental transverse TEM_{00} mode.

Keywords: self-Q-switched, 946nm laser, $Cr^{4+}Nd^{3+}$:YAG
PACC: 4255, 4270, 7845, 4260

1. Introduction

Solid diode-laser pump integrated lasers are extremely useful in the modern world, and have been highly developed because of detailed investigations in optical physics.[1−17] Studies of the self-Q-switched laser and the blue laser, especially pumped by a diode laser, are very active fields.[1−32] Diode-laser pumped solid-state lasers have better efficiency, good reliability, better integrity, easy operation, and larger emitting power. The manner of diode-laser pumping provides a number of advantages in comparison with other pumping strategies. The self-Q-switched laser of the chromium and neodymium codoped yttrium aluminum garnet crystal material ($Cr^{4+}Nd^{3+}$:YAG) is a new exciting frontier because of its good properties and usefulness.[5,6,12,19,23,27,32] It is an important device for its sensor applications, and especially for its blue frequency-doubled light applications in display, printing, biology, under-water operation, optical communication, sensing and storage. In other words, the study about the operating mechanism of the self-Q-switched diode-laser pumped microchip laser is of significance.[5−32]

This paper reports a study on the operating mechanism of the self-Q-switched diode-pumped laser made of the $Cr^{4+}Nd^{3+}$:YAG material. $Cr^{4+}Nd^{3+}$:YAG functions both as a gain medium and a saturable absorber. The presence of the saturable absorber Cr^{4+} ion allows self-Q-switched operation of the laser, which produces nanosecond pulses. Good fundamental transverse mode TEM_{00}, formed by the absorption bleaching, is observed.

2. Physical properties of the Nd^{3+}:YAG material

The $Y_3Al_5O_{12}$ (YAG) crystal is isotropic, with a space group of $Ia3d$ and a lattice constant of 1.2002nm. It possesses excellent optical, thermal and material properties. Some basic physical properties of the YAG crystal are listed in Table 1.[22,24] The Nd^{3+}:YAG material, activated by Nd^{3+} ions, is widely used in optics, especially as a material for continuous-wave, long-pulse, Q-switched, or mode-locked lasers because of its superior properties.

*Project supported by the National Natural Science Foundation of China (Grant Nos 19874033 and 10174008).

Table 1. Physical and thermal properties of YAG material at room temperature.

Molecular weight	593.7
Density	4.55 g/cm^3
Lattice constant	1.2002nm
Index of refraction	1.82 (at 1μm, 300K)
Hardness	8–8.5
Melting temperature	1950°C
Thermal expansion coefficient	7.5×10^{-6}K^{-1}
Thermal conductivity	0.14Wcm^{-1}K^{-1}
Heat capacity	88.8 Cal mole^{-1}K^{-1}
Thermal diffusivity	0.046cm^{2}s^{-1}

The usefulness of lasers with Nd^{3+} ions are decided by its electronic energy level structure,[7−10] whose outer electronic configuration is $4f^35s^25p^6$. The 4f subshell is partially filled with three electrons while the 5s and 5p subshells are filled completely. The 4f electrons of the Nd^{3+} ion behave like isolated electrons and are not heavily influenced by the outer environment. The electronic transitions in Nd^{3+}:YAG in optical wavelength ranges are characteristic of these f electrons. For a free Nd^{3+} ion, the f–f transitions are permitted only for two-photon processes. In a YAG material, however, single-photon f–f transitions are permitted also because of the orbital mixing among the electronic configuration states. As a result, the f–f transitions of Nd^{3+}:YAG have narrow fluorescence line widths. The energy levels of the Nd^{3+} ion are shown at the left-hand side of Fig. 1 schematically. The ground state is $^4I_{9/2}$ while ($^4F_{5/2}$, $^2H_{9/2}$,) and $^4F_{3/2}$ are important excited states which play a key role in laser operation. The absorption spectrum of the $Cr^{4+}Nd^{3+}$:YAG material has been measured and shown in Fig. 2. The sharp absorption lines in Fig. 2 result from the Nd^{3+} ion. Excitation of the Nd^{3+} ions mainly rely on the absorption lines of the Nd^{3+} ion, such as the lines near 750 and 810nm. The common Nd^{3+}:YAG laser wavelength at 1064nm is a result of stimulating radiation associated with the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. Another possible Nd^{3+}:YAG laser wavelength is 946nm resulting from the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ stimulating emission.[7−10,25,26] The lifetime of $^4F_{3/2}$ is about 0.2ms, which is rather long to make it a suitable up level for laser operation. It is easy to achieve a population inversion of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition for this 4-level laser system, which provides the common Nd^{3+}:YAG laser wavelength at 1064nm. On the other hand, it is difficult to realize a three-level laser system of the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition in general case, whose fluorescence is centred at 914nm, because $^4I_{9/2}$ is the ground state. However, it is possible to utilize the upper Stark sub-level of $^4I_{9/2}$ to construct a quasi-three-level laser system,[7−10,32] whose stimulated emission should provide radiated-laser at 946nm. It is necessary to have a large excitation in order to achieve $^4F_{3/2} \rightarrow {}^4I_{9/2}$ population inversion in this case. Furthermore, because the cross section for the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition ($\sigma_0 = 4\times10^{20}$cm^2)[14] is only about 1/9 that of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition,[31] the 946nm laser emission has to compete with the 1064nm laser. In our experiment, the 946nm laser is achieved by coating the cavity mirrors with films that suppress the 1064nm operation and enhance the 946nm laser.

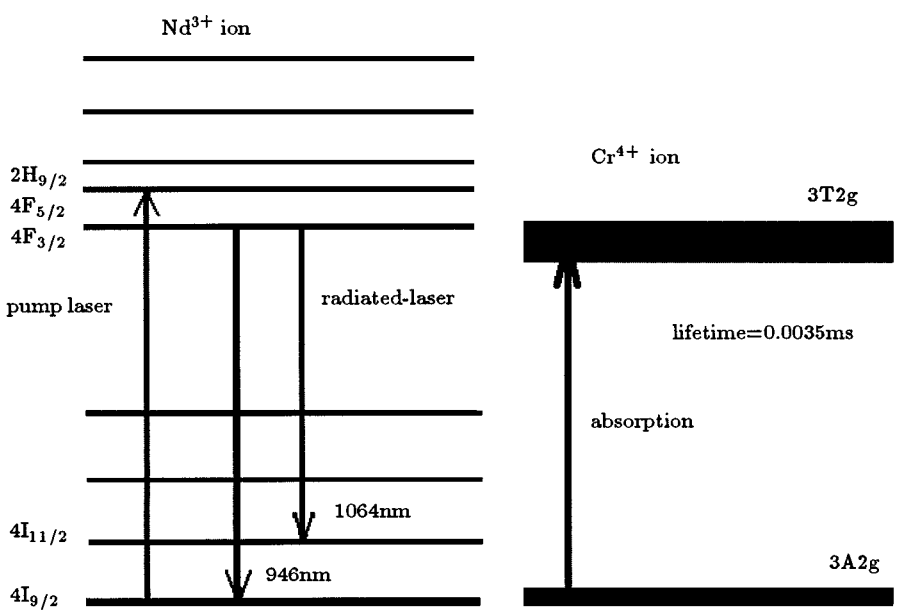


Fig.1. The energy levels of the Cr^{4+} and Nd^{3+} ion.

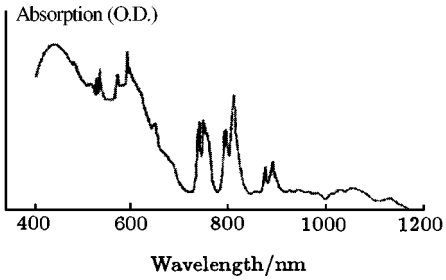


Fig.2. The absorption spectrum of the $Cr^{4+}Nd^{3+}$: YAG material.

3. Self-Q-switched mechanism of Cr^{4+}-doped YAG

The Cr^{4+}-doped YAG material is a new type of saturable absorber that could be used as a self-Q-switching material.[5,19,22,26,27] It has better properties than dyes and colour-centre materials. The measured absorption spectrum of $Cr^{4+}Nd^{3+}$:YAG is shown in Fig. 2. The wide and smooth absorption bands in Fig. 2 result from the Cr^{4+} ions. The main absorption bands of the Cr^{4+} ions are positioned at about 450, 600 and 1050nm. The electronic energy levels of the Cr^{4+} ions are shown at the right-hand side of Fig. 1.[22,24] The ground state of the Cr^{4+} ions is $^3A_{2g}$. The first excited state is $^3T_{2g}$, which is positioned at about 1050nm. The higher excited state is $^3T_{1g}$, which is positioned at about 600nm. The states $^3A_{2g}$, $^3T_{2g}$ and $^3T_{1g}$ are spin triplet states. The lifetime of $^3T_{2g}$ is about 3.5×10^{-3}ms.

The self-Q-switched mechanism of the Cr^{4+} ion comes from the interesting nonlinear optical property.[5,19,22,23,27] When the saturable absorber of the Cr^{4+} ion is added into a laser cavity, the relation between the light intensity within the cavity and the loss exhibits a colossal nonlinear phenomenon. Variation of gain ρ with time t is shown in Fig. 3. In the initial period of time $0 \rightarrow T_0$, the loss N of the system is maintained at a constant value, that is, the threshold N_{t1} for population inversion. Meanwhile, the gain ρ of the laser medium is linearly increased basically, resulting from the accumulation of absorbed pump energy. The linear absorption of the self-Q-switching medium Cr^{4+}-doped YAG is quite large because the small-signal transparency at t=0 is very small, which results in the threshold N_{t1} for population inversion is also rather high. The gain is smaller than the loss before $t = T_0$, which results in the accumulation of absorbed pump energy to a high level and is not wasted due to the non-threshold stimulated emission. When the time is longer than T_0, the gain ρ is larger than the loss. According to the definition,[20] the gain ρ of a laser is increasing laser light intensity obtained from the gain-medium. Oscillating laser could be achieved after the gain ρ is equal to or larger than loss.[20] So, the laser oscillation is established at time T_0. Then the loss of the system is decreased rapidly to a low level N_{t2} because the Cr^{4+} ion is bleached fast by large oscillating laser light within the cavity. In the period $t > T_0$, the light intensity within the cavity is enhanced super-fast due to the fast decrease of the loss. It is interesting that decreasing the loss is accelerated by increasing light intensity within the cavity, which results in the self-Q-switching operation established at about nanosecond scale $\Delta t = T_b - T_0$, and a large-pulse of monofrequency self-Q-switched laser is radiated initially. The stable transparency, which is established from the time $t = T_b$, is very large. It is about 60%–70% measured experimentally. It means that the Cr^{4+} ion is entirely bleached basically at time T_b. Then the loss of the system is kept at low level N_{t2} for about 3.5×10^{-3}ms, that is, the lifetime of first excited state $^3T_{2g}$ of the Cr^{4+} ion. This makes the Cr^{4+} ion a very good candidate of self-Q-switching for the 946nm Nd^{3+}:YAG laser. The low loss condition N_{t2} for laser oscillation begins to be satisfied from time T_b. The high N_{t1}, small N_{t2} and fast progress permit the laser system to have a good self-Q-switching. Because the accumulated energy is released by the stimulating emission of the laser, the gain reaches a maximum ρ_{max} at time T_m, thus results in the fastest enhancement of the self-Q-switched laser at time T_m.

The self-Q-switched laser is amplified continuously during the time from T_m to T_i because the gain is larger than the loss. The self-Q-switched laser reaches a maximum I_{max} at $t = T_i$ because the net gain equals zero at time T_i. The self-Q-switched laser releases the accumulated energy from T_0 to time $t = T_s$, where the large-pulse laser is finished at time T_s. Because the laser-medium is kept at low loss level N_{t2} for about 3.5×10^{-3}ms, the laser oscillation may be established again, which is not the Q-switched laser, however. It is clear that only small pulse laser or small continuous laser could be formed after the first large-pulse laser at this bleaching period. As a result, the radiated self-Q-switched laser has some jitter, which is the small pulse laser or the small continuous laser, after the large-pulse laser peak. The large-pulse laser can be achieved again only after the Cr^{4+} ion returns to the ground state and the bleaching is recovered basically.

This is just the action of self-Q-switched mechanism and is coincided with our experimental results.

In conclusion, the self-Q-switched operation of the Cr^{4+}-doped YAG material is excellent.

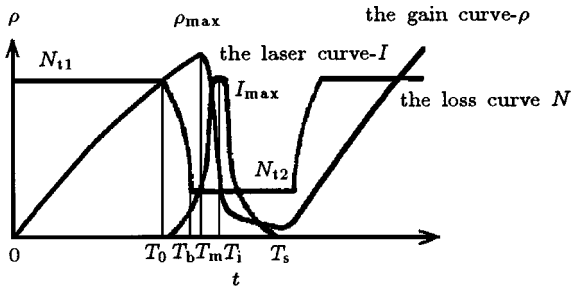


Fig.3. The schematic diagram of self-Q-switched mechanism of the $Cr^{4+}Nd^{3+}$:YAG material.

4. Principle of the $Cr^{4+}Nd^{3+}$: YAG laser

The self-Q-switched laser could be achieved within the $Cr^{4+}Nd^{3+}$:YAG material. When Cr^{4+} Nd^{3+} : YAG is optically pumped by an 808nm-laser, the Nd^{3+} ions are excited and then non-radiatively decay to the $^4F_{3/2}$ level of the Nd^{3+} ion. Strong light from the $^4F_{3/2}$ state to lower states is present within the cavity. The fluorescence could be absorbed by the Cr^{4+} ions. The long lifetime of the $^3T_2$ state of the Cr^{4+} ion is the physical cause that keeps the bleaching of the $Cr^{4+}Nd^{3+}$:YAG. An absorption bleaching is established within the $Cr^{4+}Nd^{3+}$:YAG to benefit the production of TEM_{00} mode laser. The $Cr^{4+}Nd^{3+}$:YAG is an excellent material that has a proper absorption in the whole wave range of 750–1050nm, as shown in Fig. 2. The bleaching effect is caused not only by the oscillating 946nm laser of Nd^{3+} ions but also by the 808nm pump laser. The self-Q-switched effect of the $Cr^{4+}Nd^{3+}$:YAG results from the strong oscillating laser of the Nd^{3+} ions within the cavity. The absorption bleaching results from both the oscillating laser and the pump laser, and the latter plays a more important role. It is obvious that there is a definite bleaching space distribution caused by the pump laser before the action of the oscillating laser. Both the space distribution of the bleaching and the gain of the oscillating laser are almost the same as those of the pump laser. As is well known, the power density of the pump laser decreases rapidly when it is off the largest spot. So, the oscillation of the self-Q-switched laser is initiated at the brightest spot of the pump laser when the oscillating cavity is good. The bleaching distribution caused by the pump laser will be benefited greatly further by the oscillating self-Q-switched laser. This causes the absorption bleaching close to the TEM_{00} mode further. It means that the TEM_{00} transverse mode of the oscillating laser has a loss much lower than the loss of others. Other transverse modes are suppressed by their high loss of the saturable absorber. The larger the light intensity, the more obvious the effect.[19] It can be concluded that the oscillating laser prefers to be operated with only one transverse TEM_{00} mode.

5. The experimental results and conclusion

The self-Q-switched diode-pumped 946nm laser of the $Cr^{4+}Nd^{3+}$:YAG material is studied experimentally in this paper. The 946nm laser system is optically pumped by an 808nm diode-laser, which is manufactured by the Institute of Semiconductor of Chinese Academy of Sciences. The pump diode-laser is focused onto the $Cr^{4+}Nd^{3+}$:YAG by a group of lenses. Both surfaces of the crystal are coated with the cavity films, which serve as the two cavity-mirror of the oscillating laser. The $Cr^{4+}Nd^{3+}$:YAG crystal is manufactured carefully so as to have an excellent double-parallel plane structure. Its diameter is about 5mm and the thickness is 1.5mm. The angle between both planes is smaller than $10''$. The emitted laser power of the $Cr^{4+}Nd^{3+}$:YAG is measured by an optical power-meter. The threshold power of the pump laser is about 257mW, while the largest power of the self-Q-switched 946nm laser is about 5.7mW. It is obvious that the repetition rate increases linearly with the pump laser power. Meanwhile, the peak-power and the full width at half maximum (FWHM) keep unchanged at about 150W and 4.2ns respectively, despite the large change of the pump laser. It is also found that the self-Q-switched 946nm laser is in a good fundamental transverse mode TEM_{00}.

In conclusion, the diode-pump self-Q-switched 946nm laser made of the $Cr^{4+}Nd^{3+}$:YAG crystal material has been studied especially about its physical mechanism of operation. The $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition of Nd^{3+} ion is beneficial to achieving laser oscillation in a quasi-three-level system based on coating the cavity mirrors of microchip with films that can suppress the 1064nm operation and enhance the 946nm laser. The Cr^{4+} ion is a saturable absorber. The initial loss N_{t1} is high, which acts as the threshold for

population inversion. The stable loss N_{t2} is low because the Cr^{4+} ion is acceleratively bleached by the fast enhancement of the oscillating laser. The high N_{t1}, small N_{t2} and fast progresses permit the oscillating laser of the $Cr^{4+}Nd^{3+}$:YAG to have a good self-Q-switched property whose FWHM is about 4.2ns. Its largest laser power is about 5.7mW, while its peak power is about 150W. It is proved that it is the fundamental transverse mode TEM_{00}. The good TEM_{00} transverse mode results from the absorption bleaching established by both the pump and oscillating lasers, which suppress other transverse mode and allow the oscillation only in the fundamental transverse TEM_{00} mode.

Acknowledgements

The authors would like to thank Professor Yuxin Nie, Professor Chenjia Chen, Professor Jinguang Wu, Professor Zengfu Song, Professor Naiyan Wang, Professor Guowen Wang, Professor Zizhao Gan and Professor Jiaer Chen, Professor Duanfu Xu, Professor Yanlin Ye at Peking University and so on, Professor Zhi-li Chen, Professor Shi-qu Zheng, Professor Qi Dong, Professor Dahe Liu, Professor Yan-feng Chen, Professor Ping Wang, and Professor Guo-ying Fan at Beijing Normal University and so on; Professor Yongzhen Huang at the Institute of Semiconductor Physics of Chinese Academy of Science. The authors thank Professor YX-Nie, Professor BH-Feng, Professor F-Wang, Professor HF-Li, Professor DZ-Zhang at the Institute of Physics of Chinese Academy of Science.

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