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Cr,Nd:YAG self-Q-switched laser with high efficiency output

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Abstract

The high efficient laser performance of self-Q-switched laser in the co-doped Cr^{4+}, Nd^{3+}:YAG microchip with 1.8 mm thickness was demonstrated. The slope efficiency is varied with the reflectivity of output coupler at 1064 nm, and the highest slope efficiency of 26% was obtained for 95% reflectivity of output coupler at 1064 nm. The pulse width, the single pulse energy and the pulse repetition rate for different reflectivity of the output couplers were measured, and the experimental results agree with the numerical calculations of the passively Q-switched rate equations. This can lead to develop the diode laser pumped monolithic self-Q-switched solid-state microchip lasers, especially for the intracavity frequency-doubled solid-state microchip lasers.

Keywords: Cr,Nd:YAG crystal; ; Self-Q-switched laser

1. Introduction

Diode-pumped Q-switching solid-state lasers have been demonstrated to have high efficiency, high average power and high energy per pulse. It is well known that Q-switching lasers can be applied widely in: lidar, remote sensing, pollution detection, non-linear-optical process, and material processing. In recent years, Cr^{4+}-doped crystals have attracted a great deal of attention as passive Q-switches [1–8]. In comparison with previously used saturable absorber such as dyes [9] and LiF:F_2^- color center crystals [10]. Cr^{4+}-doped crystals are more photochemically and thermal stable, have a higher damage threshold and large absorption cross-section, low saturable intensity and high damage threshold. Especially, Cr^{4+}-doped YAG crystal, owing to its easy growth of high quality and high concentration single crystal and can be co-doped with gain medium to form self-Q-switched laser crystal [5,11–14], has attracted a great deal of interest in recent years. Shouhuan Zhou et al. [5,11–14] first studied the self-Q-switched laser performance of LD pumped Cr,Nd:YAG crystal, the pump source they used is the quasi-CW mode AlInGaAs diode laser, using different laser cavities, they obtained the Q-switched pulse energy of 7 μJ and a full-width at half-maximum (FWHM) duration of 3.5 ns [5], pulse energy of 10 μJ and a FWHM duration of 3.5 ns [11], pulse energy of 3 μJ and a FWHM duration of 30 ns, and pulse energy of 8 μJ and a FWHM duration of 270 ps [14], respectively. The highest net optical conversion efficiency they obtained using different laser cavities is 8%. Dong et al. [15] also reported the LD pumped Cr,Nd:YAG self-Q-switched laser, but the optical conversion efficiency is about 13% and slope efficiency is 20%. It is well known that the distribution coefficient of Nd^{3+} ions in YAG is about 0.18, so the concentration of Nd in YAG cannot be high and if the concentration is higher than 1 at%, the distribution of Nd along the radius and growth axe is not unity. This will degrade the laser performance of Cr,Nd:YAG crystal. So the Cr,Nd:YAG crystal with lower concentration of chromium and neodymium (0.5 at% Nd and 0.01 at% Cr) was grown and the spectral properties and laser performance were studied. In this paper, we present the performance of Ti:sapphire laser pumped Cr,Nd:YAG self-Q-switched laser. For different reflectivity of the output couplers, the single pulse energy, the pulse width and repetition rate of 1064 nm laser have been measured. Meanwhile, the coupled equations of self-Q-switched laser were given and the numerical solutions of the equations agree with the experimental results.

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2. Experiments

2.1. Crystal growth and spectral analysis

The Cr,Nd:YAG crystal used in experiment was grown by using the standard Czochralski (CZ) method. Cr^{4+} is regarded to be substituted into distorted tetrahedral Al site, therefore a charge compensator is required and $CaCO_3$ was added to as a charge compensator. The concentration of Cr and Nd in Cr,Nd:YAG crystal are 0.01 at% and 0.5 at% respectively. The absorption spectra were measured using a Cary 500 Scan UV–Vis–NIR spectrophotometer. Emission spectra were measured between 820 nm and 1520 nm. The excitation source was a diode laser operating at 808 nm. The excitation signal was monitored during the experiment with a silicon (Si) detector. The resolution of this detection system was about 0.4 nm. And lifetime of Cr,Nd:YAG was also measured.

2.2. Laser experiment

The schematic of CW Ti:sapphire laser pumped the Cr,Nd:YAG self-Q-switched laser cavity is shown in Fig. 1. A Cr,Nd:YAG crystal was polished to a planar–planar geometry. The end surface of a $6 \times 6 \times 1.8\ \text{mm}^3$ Cr,Nd:YAG laser crystal, coated for high transmission at 808 nm and total reflection at 1064 nm, acted as one of the resonator mirrors. The other surface of the crystal is coated for high transmission at 1064 nm and total reflection at 808 nm. A spherical concave mirror, which has a 50 mm radius of curvature, coated for 99%, 97% and 95% reflection at 1064 nm respectively, acts as output coupler. The overall cavity length is 50 mm. The misalignment of the axes of the two mirrors is measured to be less than 0.3°. The laser operation was performed at 278 K by using the constant-temperature water-cooled circulation with a copper surface. The Q-switched pulses was recorded using a fast Si PIN detector with a 1.5 ns rise time and a Tektronix TDS 380 digitizing oscilloscope with 400 MHz sampling rate in the single-shot mode. The output power was measured using a laser power meter. The Ti:sapphire laser output, after beam shaping with a focal lens, is focused onto a spot with a diameter of 50 µm. The Ti:sapphire laser is operated in the CW mode, and after focal lens the loss is approximately 8%.

3. Results and discussion

The room temperature absorption spectrum and emission spectrum are showed in Fig. 2 and Fig. 3, respectively. The absorption coefficient is $3.5\ \text{cm}^{-1}$ at the pumping wavelength of 808 nm and is $0.56\ \text{cm}^{-1}$ at 1064 nm. The emission cross-section is $2.35 \times 10^{-19}\ \text{cm}^2$ at 1064 nm, the lifetime is about 210 µs, a little shorter than that of Nd:YAG (230 µs).

With Cr,Nd:YAG crystal as the active medium, under the CW pumping, the Q-switched laser was obtained. In our experiments, to optimize the laser performance of self-Q-switched operation, three output couplers with reflectivity of $R = 99\%$, 97% and 95% were used. The best results were achieved for the output coupler with reflectivity of 95%. The average output power, pulse repetition rate and pulse width (FWHM) in a self-Q-switched mode were measured as functions of the incident pump power. The pulse energy was determined from the average output power and pulse repetition rate. The peak power was determined from the pulse energy and pulse width. Fig. 4 shows the average output power, pulse energy and peak power as functions of the incident pump power for output couplers of reflectivity $R = 99\%$, 97% and 95%, respectively. It can be seen that the average output power depends linearly on the incident pump power for three reflectivities of output couplers. Form the linear relationship of average output power and incident pump power, the threshold pump power and slope efficiency can be extrapolated. The threshold pump powers are approximately 14.1, 23.4 and 27.6 mW with a decrease in the reflectivity of output couplers from 99% to 95%. The slope efficiencies for three output couplers are 12%, 18% and 26%, respectively. And the highest optical efficiency (the ratio of average output power and the incident pump power) of the self-Q-switched lasers is approximately 21.6% for the output coupler of 95% reflectivity. The highest average output power of 80 mW at 1064 nm is obtained with the 95% output coupler at an incident pump power of 370 mW. We obtained 1.75 µJ self-Q-switched pulses with a pulse width of 50 ns, resulting in a peak power of 35 W at a repetition rate of 45 kHz with $R = 95\%$ output coupler at 370 mW incident pump power (Fig. 4).

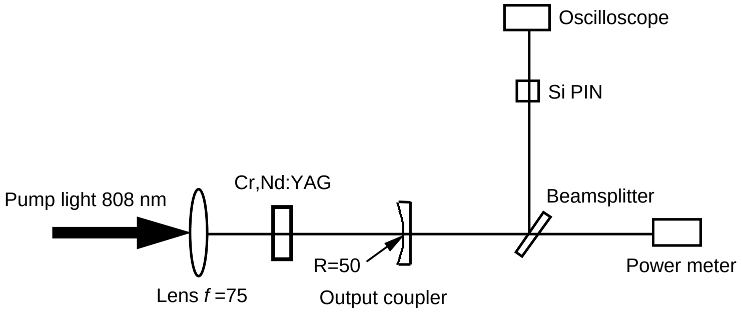

Fig. 1. The experimental setup of Ti:sapphire laser pumped Cr,Nd:YAG self-Q-switched laser.

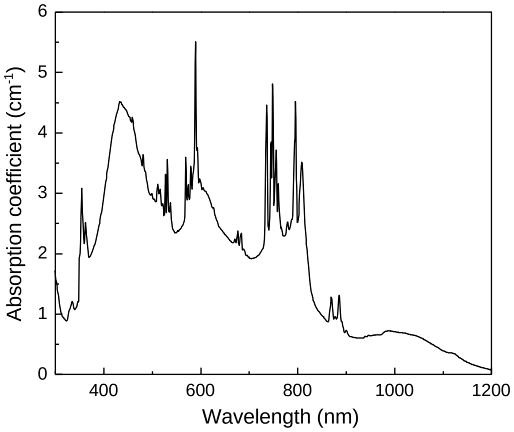

Fig. 2. The absorption spectrum of Cr,Nd:YAG crystal at room temperature.

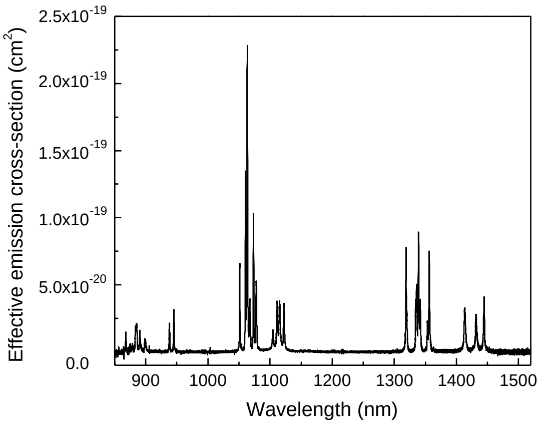

Fig. 3. The emission spectrum of Cr,Nd:YAG at room temperature.

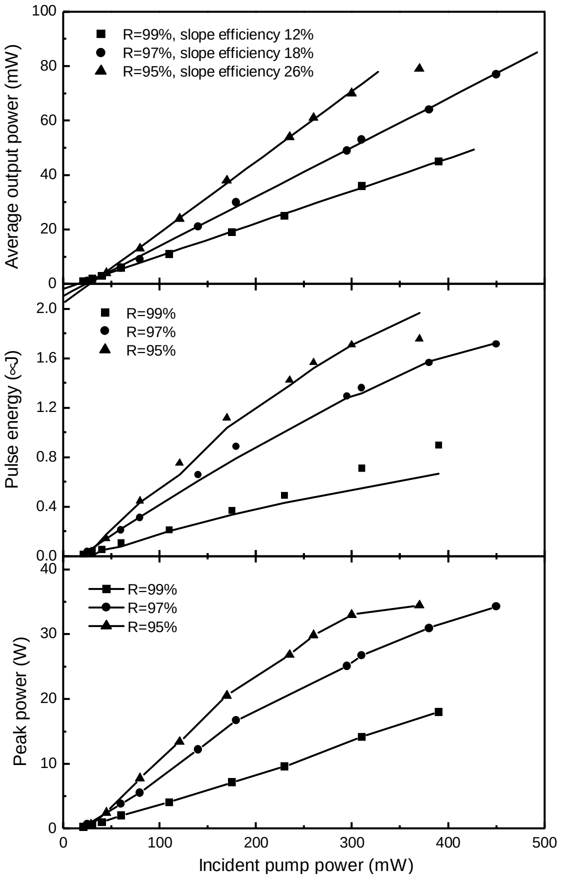

Fig. 4. Average output power, pulse energy and peak power versus incident pump power of Cr,Nd:YAG self-Q-switched laser for three different output couplers.

Fig. 5 shows the pulse repetition rate and the pulse width as functions of the incident pump power for three reflectivities of output couplers. The pulse repetition rate (f) and pulse width (t_p) are another two important parameters of passively Q-switched lasers. The pulse repetition rate, the pulse width are mainly determined by the output coupler reflectivity R while incident pump power also has a perceptible effect on these parameters of the self-Q-switched laser. For a certain reflectivity of output coupler, the repetition rate increases linearly with the increasing pumping power, as expected from the passively Q-switched theory; the repetition rate increases a little bit with the decreasing of the reflectivity of output couplers for a certain pump power level. For three different output couplers, the pulse width decreases with the increasing incident pump power, and pulse width keeps the same value of 50 ns at the higher incident pump power. For the output coupler with $R = 99\%$, we obtained 50 ns pulses with a repetition rate of 40 kHz at a maximum incident pump power of 390 mW. The corresponding pulse energy and peak power were approximately 0.9 μJ and 18 W, respectively. As the output couplers with a lower reflectivity were used, the higher repetition rate was obtained. We generated a pulse width of 50 ns with a repetition rate of 45 kHz by using output coupler with $R = 97\%$, which corresponds to a pulse energy of 1.71 μJ and a peak power of 34 W at maximum incident pump power of 450 mW. The highest pulse energy and peak power were generated when we used the output coupler with $R = 95\%$. At a maximum incident pump power of 370 mW, self-Q-switched pulses with pulse width of 50 ns and repetition rate of 45 kHz were obtained. The corresponding highest pulse energy and peak power are 1.75 μJ and 35 W. Fig. 6 shows a typical single self-Q- switched laser pulse with energy of 1.75 μJ and a pulse width of 50 ns at pulse repetition rate of 45 kHz for output coupler with $R = 95\%$ at the maximum incident pump power of 370 mW, the corresponding peak power is 35 W.

The coupled rate equations of photon density in the self-Q-switched resonator, which includes the excited-state absorption of the saturable absorber, are as following [16]:

$$\frac{d\phi}{dt} = \frac{\phi}{t_r}\left(2\sigma n l - 2\sigma_g n_g l_s - 2\sigma_e n_e l_s - \ln\left(\frac{1}{R}\right) - L\right), \quad (1)$$

$$\frac{dn}{dt} = -\gamma\sigma c\phi n - \frac{n}{\tau} + W_p, \quad (2)$$

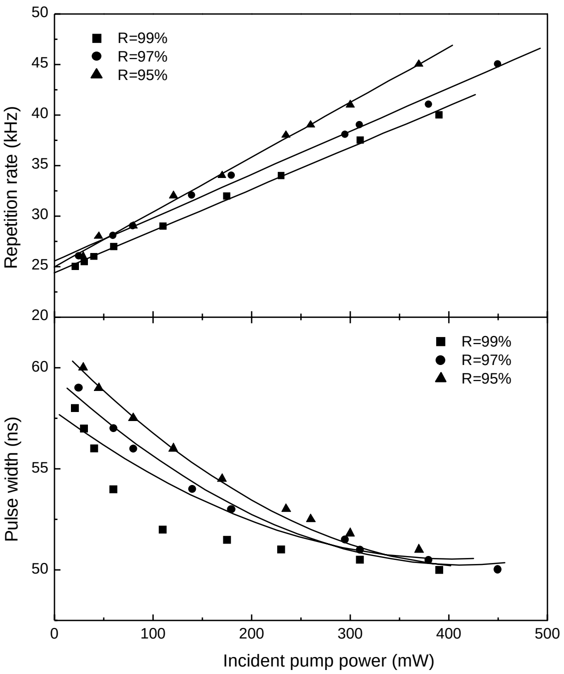

Fig. 5. Repetition rate and pulse width versus the incident pump power Cr,Nd:YAG self-Q-switched laser for three different output couplers.

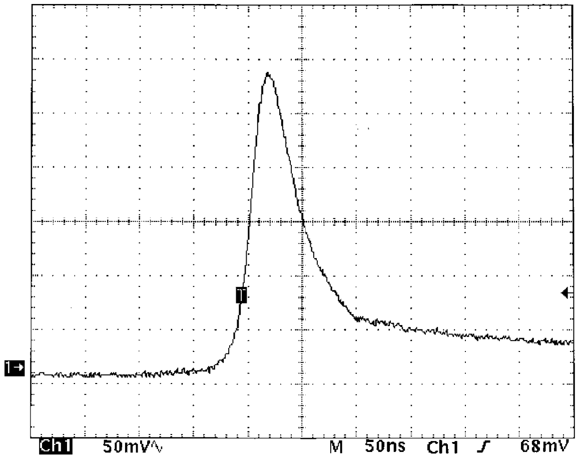

Fig. 6. Oscilloscope trace of a single self-Q-switched laser pulse with a pulse width of 50 ns at 45 kHz repetition rate for output coupler with $R = 95\%$ at incident pump power of 370 mW.

$$\frac{dn_g}{dt} = -\sigma_g c\phi n_g + \frac{n_{s0} - n_g}{\tau_s}, \tag{3}$$

$$n_g + n_e = n_{s0}, \tag{4}$$

where ϕ is the photon density in the laser cavity of optical length l', n the population inversion density of the laser rod, σ is the stimulated emission cross section of the laser crystal, t_r the cavity round-trip time, $t_r = (2n_1 l + 2(l' - l))/c$, n_1 the refractive index of the laser crystal, l the length of the laser crystal, l' the cavity length, c the speed of the light, σ_g the absorption cross-section of ground state of the saturable absorber, σ_e the absorption cross-section of the excited state, l_s the length of the saturable absorber, for Cr,Nd:YAG self-Q-switched laser crystal, $l_s = l$, n_g and n_e are the absorber ground state and excite state population density, respectively, n_{s0} the total population density of the saturable absorber, R the reflectivity of the output coupler, L is the nonsaturable intracavity round-trip dissipative optical loss, γ the inversion reduction factor, W_p the volumetric pump rate into the upper laser level and is proportional to the CW pump power, τ the lifetime of the upper laser level in the gain medium.

With CW pumping, the laser will passively Q-switched as soon as the gain exceeds the combined saturable and unsaturable losses in the resonator. As the incident pump power is increased, the laser eventually reaches a threshold condition and begins to repetitively Q-switched with a time interval between pulses, t_c. The pulse energy and pulse repetition rate will be increased and the pulse width will be decreased with further increasing of the incident pump power.

For CW pumped repetitive Q-switching laser at a repetition rate f, the maximum time available for the inversion to build up between pulses is $t_c = 1/f$. Therefore, the initial inversion density of the Q-switch under the influence of the incident pump power is $n_i = n_{cw} - (n_{cw} - n_f)\exp(-1/\tau f)$ in order to have the inversion return to its original value after each Q-switch cycle, where n_{cw} is the CW pumping inversion density inside the resonator, $n_{cw} = W_p \tau n_{tot}$, W_p is the volumetric pump rate into the upper laser level and is proportional to the CW pump power, $W_p = P_p / h\nu_p A l$, P_p is the incident pump power, $h\nu_p$ is the pump photon energy, A is the pump beam area, l is the length of the gain medium; n_{tot} is the total ground state density of gain medium.

The internal optical loss of the laser resonator can be determined by using of the logarithm of reflectivity of the different output couplers and the threshold pump power for each output coupler, as described following [9],

$$-\ln R = 2kP_{th} - L, \tag{5}$$

where R is the reflectivity of the output coupler, k is the pumping coefficient, and P_{th} is the threshold pump power. By using the measured threshold pump powers for three different output couplers, the internal optical loss of self-Q-switched Cr,Nd:YAG resonator can be calculated as $L = 0.0323$.

The output pulse energy E, peak power P and pulse width τ_p of self-Q-switched Cr,Nd:YAG laser can be written as [17]

$$E = \frac{h\nu A}{2\sigma\gamma} \ln\left(\frac{1}{R}\right) \ln\left(\frac{n_i}{n_f}\right), \tag{6}$$

$$P = \frac{h\nu A l}{\gamma t_r} \ln\left(\frac{1}{R}\right) \left\{ n_i - n_t - n_{t0} \ln\left(\frac{n_i}{n_t}\right) - (n_i - n_{t0}) \left[1 - \left(\frac{n_t}{n_i}\right)^{\alpha}\right] \frac{1}{\alpha} \right\}, \tag{7}$$

Table 1
The parameters of Cr,Nd:YAG for calculating the theoretical results

σ_g	8.7×10^{-19} cm^2
σ_e	2.2×10^{-19} cm^2
σ	2.35×10^{-19} cm^2
τ	210 μs
τ_s	3.4 μs
γ	0.6
T_0	90%
l	0.18 cm
A	3.927×10^{-5} cm^2
t_r	0.343 ns
L	0.0323
$h\nu_p$	2.46×10^{-19} J
$h\nu$	1.86×10^{-19} J

$$\tau_p \approx \frac{E}{P}, \tag{8}$$

where $h\nu$ is the photon energy, A is the active area of the pump beam in the laser medium, n_i, n_t, n_f are the population inversion densities at the start of Q-switching, the point of maximum power and the end of the Q-switched pulse, respectively; α is a synthetic dimensionless parameter, $\alpha = \sigma_g/\gamma\sigma$, n_{t0} corresponds to the n_t in the case of $\alpha \to \infty$,

$$n_{t0} = \frac{n_{th}(\ln(1/R) + (\sigma_e/\sigma_g)\ln(1/T_0^2) + L)}{\ln(1/R) + \ln(1/T_0^2) + L},$$

where n_{th} is the population inversion density at threshold,

$$n_{th} = \frac{\ln(1/R) + \ln(1/T_0^2) + L}{2\sigma l},$$

T_0 is the initial transmission of the saturable absorber.

Eqs. (6) and (7) contain three unknown variables, n_i, n_f and n_t. These unknown variables can be obtained through numerical solving Eqs. (1)–(3), the related parameters used the numerical solution of Eqs. (1)–(3) are listed in Table 1. The solid lines in Figs. 4 and 5 show the calculated values of single pulse energy and pulse width for output couplers with three different reflectivities, respectively. It can be seen from Figs. 4 and 5 that the theoretical calculations are in good agreement with the experimental results. From the theoretical calculations and the experimental results, we can see that for a certain output coupler, the laser characteristics of the self-Q-switched Cr,Nd:YAG laser depend strongly on the incident pump power and the output coupler reflectivity. With the increase of the incident pump power, the pulse energy increase and pulse width decreases. However, there are also some discrepancies between the calculations and the experimental results, especially for output coupler of 99% reflectivity, with the increase of the incident pump power, the difference between the calculated pulse energy and measured energy increases, this may be caused by the inaccurately the output coupler reflectivity, the reflectivity is not actually 99%, may be less. Also the related parameters in Table 1 used for calculation are not well known.

According to the theoretical analysis, when the pump power well in excess of the pump threshold, the pulse repetition rate, f, should increase linearly with the pump power, and the pulse repetition rate of a continuously pumped passively Q-switched laser can be written as [17]:

$$f = \left[\tau \ln\frac{(W_p/W_{pth} - \beta}{W_p/W_{pth} - 1}\right]^{-1}, \tag{9}$$

where $\beta = 1-(f_a/\gamma)(1-n_f/n_i)$, $W_{pth} = n_i/\tau$, W_p corresponds to the population density pumped to the upper laser level per unit time, W_{pth} is the threshold of W_p, τ is the upper level laser lifetime. The numerical solutions of Eqs. (1), (2) and (3) may obtain a train of laser pulses under the CW pump power, from Eq. (9), the pulse repetition rate can be calculated for different output couplers. The solid lines in Fig. 5 show the calculated pulse repetition rate versus the incident pump power for different output couplers. From Fig. 5, we can see that the experimental results agree with the prediction of the theoretical calculation.

4. Conclusion

In conclusion, the high efficient laser performance of self-Q-switched laser in the co-doped Cr^{4+}, Nd^{3+}:YAG microchip with 1.8 mm thickness was demonstrated. The slope efficiency is varied with the reflectivity of output coupler at 1064 nm, and the highest slope efficiency of 26% was obtained for 95% reflectivity of output coupler at 1064 nm. And the pump power thresholds for three output coupler are very low. The pulse width, the single pulse energy and the pulse repetition rate for different reflectivity of the output couplers were measured under the influence of the incident pump power, and the experimental results agree with the numerical calculations of the passively Q-switched rate equations. For this kind of the laser cavity design, we can put a second harmonic generator such as KTP or KDP crystals into the laser cavity, to realize the intracavity frequency-doubling, so this can lead to develop the diode laser pumped monolithic self-Q-switched solid-state microchip lasers, especially for the intracavity frequency-doubled solid-state microchip lasers. The research on the intracavity frequency-doubled self-Q-switched solid-state lasers is under progress.

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