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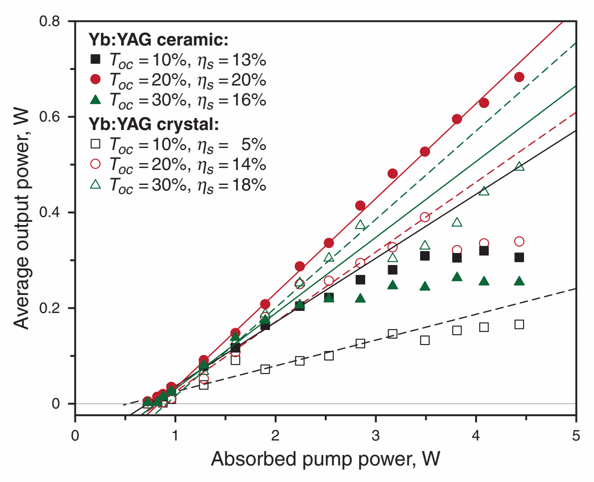
**Abstract:** Enhancement of laser-diode pumped self-Q-switched Cr, Ca, and Yb$^{3+}$ ions co-doped YAG (Cr,Yb:YAG) lasers by bonding Yb:YAG ceramic to increase pump power absorption efficiency have been demonstrated for the first time to our best knowledge. Efficient Cr,Yb:YAG self-Q-switched laser performance has been achieved by bonding Yb:YAG ceramic. The effect of transmission of output coupler ($T_{OC}$) on the laser performance has been investigated and found that the best laser performance was achieved with $T_{OC} = 20\%$ for Yb:YAG ceramic. Slope efficiency of 20% was achieved with $T_{OC} = 20\%$ for Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic. Maximum average output power of 683 mW was measured at absorbed pump power of 4.5 W; the corresponding optical-to-optical efficiency is 15.2%. The output laser pulse characteristics were compared for Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal under different transmission of output coupler. For the same $T_{OC}$, the laser performance of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic is better than that by bonding Yb:YAG crystal.



Average output power of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal as a function of the absorbed pump power for different transmission of output coupler, $T_{OC}$

# Comparative study on enhancement of self-Q-switched Cr,Yb:YAG lasers by bonding Yb:YAG ceramic and crystal

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**Key words:** Cr,Yb:YAG; self-Q-switched; Yb:YAG ceramic; solid-state lasers

## 1. Introduction

Diode laser pumped passively Q-switched solid-state lasers are compact and robust lasers with high pulse energies and peak powers in a diffraction-limited output beam, and have many applications such as remote sensing, range finders, pollution detection, lidar, material processing, medical systems, laser ignition, and so on [1–3]. The passively Q-switched lasers are usually constructed by using a thin gain medium bonded with saturable absorber such as a semiconductor saturable-absorber mirror (SESAM) [4], bulk Cr$^{4+}$-doped crystals by co-doping Ca$^{2+}$ ions or Mg$^{2+}$ ions as compensating chargers [5,6], or Cr$^{4+}$:YAG films deposited on the gain medium by molecular beam epitaxy (MBE) [7]. Compared with SESAM or the saturable absorber film deposited on the surface of the gain medium, Cr$^{4+}$-doped bulk crystals as saturable absorber have several advantages: high damage threshold, low cost, and simplicity. The other advantage of Cr$^{4+}$-doped bulk crystals is that self-Q-switched

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laser materials can be fabricated by co-doping Cr ions, $Ca^{2+}$ ions as compensating charger to form $Cr^{4+}$ ions in oxygen atmosphere, and lasants in YAG. Cr, Ca, and Nd ions co-doped YAG (Cr,Nd:YAG) and Cr, Ca, and Yb co-doped YAG (Cr,Yb:YAG) self-Q-switched lasers have been demonstrated [8–10]. The low concentration of $Nd^{3+}$ ions in Cr,Nd:YAG crystal limits the laser operation. Efficient laser operation requires absorbing sufficient pump power with short crystal length; a high concentration microchip laser material is required to realize subnanosecond laser operation. Compared with Nd:YAG laser material, Yb:YAG crystal has several advantages such as a long storage lifetime (951 $\mu$s) [11], a very low quantum defect (8.6% with pump wavelength of 941 nm and laser wavelength of 1030 nm), resulting in three times less heat generation during lasing than comparable Nd-based laser systems [12], broad absorption bandwidth and less sensitive to diode wavelength specifications [13], a relatively large emission cross section [14] suitable for Q-switching operation, and easy growth of high quality and moderate concentration crystal without concentration quenching [15]. Temperature dependent emission cross section of Yb:YAG materials [14] provides another flexible design for efficient operation of cryogenically-cooled Yb:YAG lasers [16]. Highly efficient intracavity frequency-doubled Yb:YAG lasers have been demonstrated recently [17–20]. Highly efficient laser performance of Yb:YAG at 1048 nm under 968 nm laser-diode pumping has been also demonstrated [21], and efficient continuous wave (CW) frequency doubling of Yb:YAG laser under 968 nm pumping has also been demonstrated [22]. Frequency doubling of Yb:YAG lasers at 515 nm matches the highest power line of Ar-ion lasers, thereby leading to the possibility of an all solid-state replacement [23]. Cr,Yb:YAG crystals have been grown successfully and optical properties of these self-Q-switched laser materials have been investigated [24,25]. The self-Q-switched Cr,Yb:YAG laser was first demonstrated using a Ti:Sapphire laser as pump source [10]. The laser-diode pumped self-Q-switched laser pulse output with pulse width of 0.5 ns was achieved with 750 $\mu$m thickness Cr,Yb:YAG crystal [26], however the average output power was very low and coating of the crystal was damaged very quickly, so this laser can not be used in practice. Recently, laser-diode pumped Cr,Yb:YAG microchip laser with pulse width of 440 ps, peak power over 53 kW has been demonstrated [27]. However, owing to co-doping of chromium ions with Yb ions into YAG host, the fluorescence lifetime decreases [25] with increase of Cr concentration and there is strong absorption (about 60% of that around 1 $\mu$m) of pump power by $Cr^{4+}$ ions at pump wavelength (around 940 nm) owing to the broad absorption spectrum of $Cr^{4+}$:YAG from 800 to 1300 nm [28,29]. The absorbed pump power threshold is high due to the high intracavity loss induced by the defects introducing Cr ions into Yb:YAG crystal for compact Cr,Yb:YAG microchip laser. The undesirable absorption at pump wavelength of 940 nm for Cr,Yb:YAG self-Q-switched laser crystal limits the laser performance or even causes Cr,Yb:YAG crystal no lasing with high Cr concentration [25]. Efficient, nanosecond self-Q-switched Cr,Yb:YAG by bonding Yb:YAG crystal has been demonstrated recently and optical-to-optical efficiency of 20% with respect to the absorbed pump power was achieved [30]. This opens a new way to construct compact, robust, efficient Cr,Yb:YAG self-Q-switched lasers by bonding YAG materials. Besides efficient laser performance has been achieved in Yb:YAG crystal, efficient mid-infrared laser performance has also been achieved with other rare earths doped YAG laser crystals, such as mid-infrared Q-switched Er:YAG lasers for medical applications [31] and resonant pumped tunable Ho:YAG laser oscillating at 2 $\mu$m [32]. The efficient laser performance of laser-diode pumped rare-earths such as Yb, Er, Ho, and so on doped YAG laser materials provides more flexible applications.

In the past decade, high quality transparent Yb:YAG ceramics have been fabricated and efficient laser operation has been demonstrated [33]. Comparative investigation of laser performance of Yb:YAG ceramics and crystals has been done and results show that Yb:YAG ceramics provide comparable or better laser performance comparing to their counterpart Yb:YAG crystals doped with different Yb concentrations [34]. Efficient laser performance of heavy doped Yb:YAG ceramics has been demonstrated recently [35,36]. High power laser-diode pumped Yb:YAG lasers based on Yb:YAG ceramics and crystals have been demonstrated with different laser resonator configuration such as thin disk lasers [37–40], rod lasers [41], microchip lasers [33,42], and slab lasers [43]. Yb:YAG ceramics have been successfully used to generate very-high order Laguerre-Gaussian modes by using a simple short-focus plano-convex glass lens [44] and circular modes by using a spherical intracavity lens [45]. Actively Q-switched Yb:YAG lasers have been demonstrated recently with electro-optical and acoustic-optical modulators [46,47] and show that Yb:YAG is an attractive laser material for laser-diode pumped all solid-state Q-switched lasers, especially for high energy application. Passively Q-switched Yb:YAG/$Cr^{4+}$:YAG all-ceramics lasers have been demonstrated [48] and highly efficient, subnanosecond pulse width and high peak power laser operation has been achieved in Yb:YAG/$Cr^{4+}$:YAG composite ceramics [49,50]. Cr,Yb:YAG self-Q-switched ceramics have been fabricated with ceramic sintering technology [51]. It is very promising to fabricate composite Yb:YAG/Cr,Yb:YAG ceramics for efficient self-Q-switched lasers by ceramics sintering technology. Therefore it is worthy to investigate the laser performance by bonding Yb:YAG ceramic with Cr,Yb:YAG self-Q-switched laser crystal.

Here we report the enhancement of Cr,Yb:YAG self-Q-switched laser performance by bonding Yb:YAG ceramic to a self-Q-switched Cr,Yb:YAG crystal. Efficient, high repetition rate, nanosecond pulse width Cr,Yb:YAG self-Q-switched lasers have been demonstrated by bonding Yb:YAG ceramic for the first time to our best knowledge. The effects of the transmission of output coupler

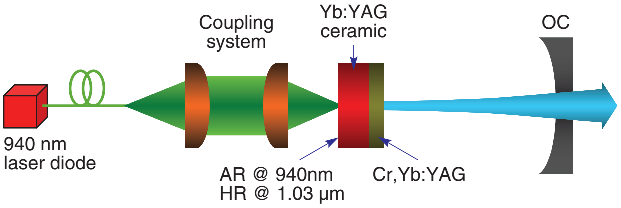

**Figure 1** Schematic diagram of experimental setup for laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched laser. OC is the output coupler

($T_{OC}$) and pump power on the laser performance of laser-diode end-pumped Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal were investigated. Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic provide better performance than those by bonding Yb:YAG crystal.

## 2. Experimental setup

The schematic diagram of experimental setup for enhancement of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic is shown in Fig. 1, which is similar to that used in the experiments of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG crystal [30]. A plane-parallel 1-mm-thick Yb:YAG ceramic plate doped with 9.8 at.% $Yb^{3+}$ ions was used as gain medium to absorb main portion of the pump power. One surface of the Yb:YAG ceramic was coated with anti-reflection at 940 nm and highly reflection at 1030 nm to act as a cavity mirror of the laser. The other surface was coated with anti-reflection at 1030 nm to reduce the intracavity loss. An uncoated 0.5-mm thick Cr,Yb:YAG crystal doped with 0.025 at.% Cr and 10 at.% $Yb^{3+}$ ions was attached together to Yb:YAG ceramic to conduct self-Q-switched laser oscillation and further absorb residual pump power for enhancing laser performance. The initial transmission of Cr,Yb:YAG crystal was estimated to be 94% by measuring the absorption spectrum of Cr,Yb:YAG around 1 $\mu$m. The mechanically bonded Yb:YAG ceramic and Cr,Yb:YAG crystal were held between two copper blocks. Five concave mirrors with 70-mm curvature and different transmissions ($T_{OC}$) of 10, 20, 30, 40, and 50% at 1030 nm were used as output couplers. The cavity length is 70 mm. A fiber-coupled 940 nm laser diode with core diameter of 200 $\mu$m and numerical aperture of 0.22 was used as the pump source. Two lenses with 8-mm focal length were used to focus the pump beam on the Yb:YAG ceramic rear surface, the diameter of the pump beam spot was measured to be 160 $\mu$m. The Cr,Yb:YAG self-Q-switched lasers enhanced by bonding Yb:YAG ceramic operated at room temperature without active cooling. The laser emitting spectra were measured with ANDO (AQ6317B) optical spectral analyzer. Average output power and pulse characteristics were measured with a 3M power meter and 400 MHz Tektronix digital oscilloscope, respectively. For comparison of the laser performance of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal, a 1-mm-thick Yb:YAG crystal doped with 10 at.% Yb was used in the laser experiments.

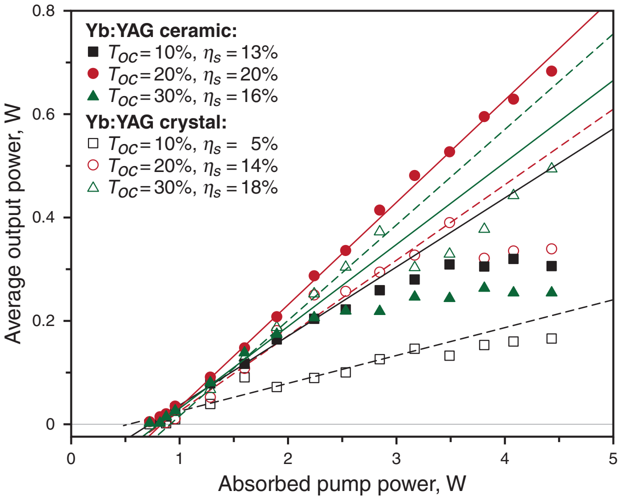

**Figure 2** Average output power of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal as a function of the absorbed pump power for different transmission of output coupler, $T_{OC}$. The lines show the linearly fitting of experimental data for different transmission of output couplers

## 3. Experimental results and discussion

Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic were obtained with $T_{OC} = 10$, 20, and 30%, we did not obtained lasing by using $T_{OC} = 40$ and 50%, this may be caused by the large loss introducing by the large transmission of the output coupler. The average output power of Cr,Yb:YAG self-Q-switched laser with bonding Yb:YAG ceramic as a function of the absorbed pump power for different output couplings ($T_{OC}$) is shown in Fig. 2, together with the average output power of Cr,Yb:YAG self-Q-switched laser with bonding Yb:YAG crystal under the same $T_{OC}$. The absorbed pump power thresholds of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic are quite similar (about 0.72 W) for different output couplings. The average output power increases nearly linearly with the absorbed pump power when the absorbed pump power is well above the pump power threshold for different $T_{OC}$. The average output power increases linearly with absorbed pump power for $T_{OC} = 20\%$. However, the average output power increases linearly with absorbed pump power at low pump power levels and tends to increase slowly when the absorbed pump power is higher than 3 W for $T_{OC} = 10\%$,

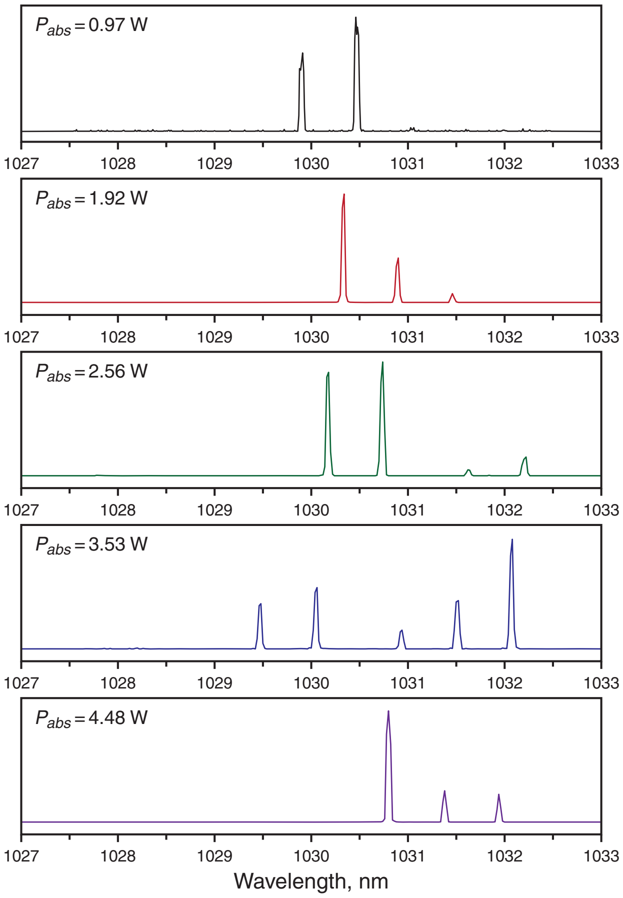

**Figure 3** Typical laser emitting spectra of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic under different pump power levels for $T_{OC} = 20\%$

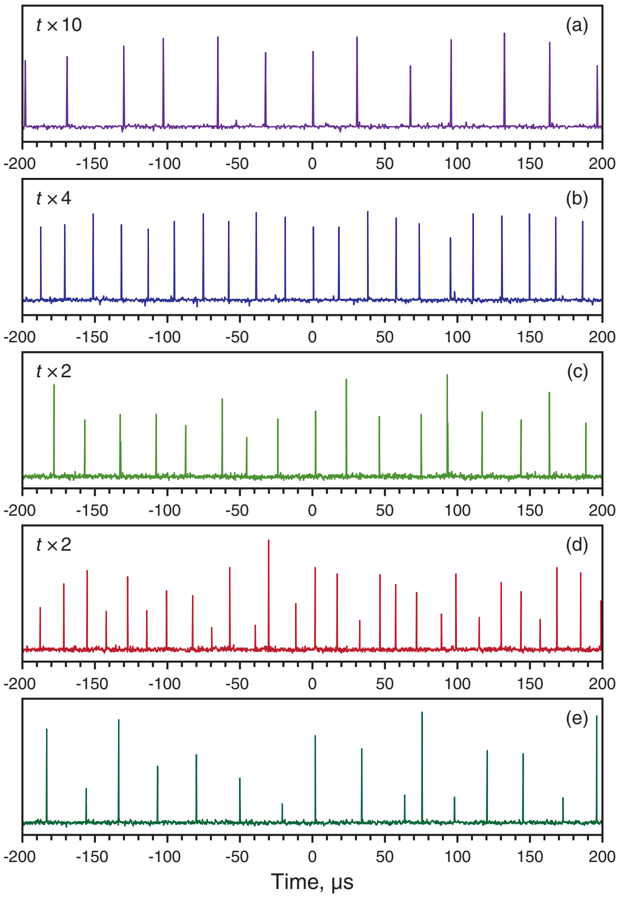

**Figure 4** Typical pulse trains of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic under different absorbed pump power levels for $T_{OC} = 20\%$

and 2.5 W for $T_{OC} = 30\%$. The output power tends to be saturated with further increase of pump power owing to the thermal effect of Yb:YAG ceramic under high pump power. The slope efficiencies were measured to be about 13, 20, and 16% for $T_{OC} = 10$, 20, and 30%, respectively. Maximum average output power of 683 mW was achieved at absorbed pump power of 4.5 W with $T_{OC}$=20%, corresponding optical-to-optical efficiency of 15% was achieved. There is an optimum transmission of output coupler (about $T_{OC} = 20\%$) for Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic. Further increase or decrease of $T_{OC}$, the performance of Cr,Yb:YAG self-Q-switched lasers with bonding Yb:YAG ceramic is getting worse at high pump power levels.

For Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG crystal, the average output power increases with the transmission of output couplers under the same pump power level. The absorbed pump power thresholds (about 0.97 W) are higher than those by bonding Yb:YAG ceramic. The slope efficiencies were measured to be about 5, 14, and 18% for $T_{OC} = 10$, 20, and 30%, respectively. Maximum average output power of 500 mW was achieved at absorbed pump power of 4.5 W with $T_{OC} = 30\%$, corresponding optical-to-optical efficiency of 11%. The output power tends to be saturated with further increase of pump power owing to the thermal effect of Yb:YAG crystal under high pump power. Laser performance of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal is better than that obtained in laser-diode pumped monolithic Cr,Yb:YAG self-Q-switched lasers with the same plano-concave cavity [52]. The enhancement of Cr,Yb:YAG self-Q-switched laser performance by bonding Yb:YAG ceramic and crystal is attributed to the increase of inversion population with Yb:YAG/Cr,Yb:YAG bonding configuration [30].

The laser emitting spectra show that the Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic oscillate in multi-longitudinal-mode for different output couplings. And the number of longitudinal modes increases with absorbed pump power. Fig. 3 shows the laser emitting spectra of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic under different absorbed power levels

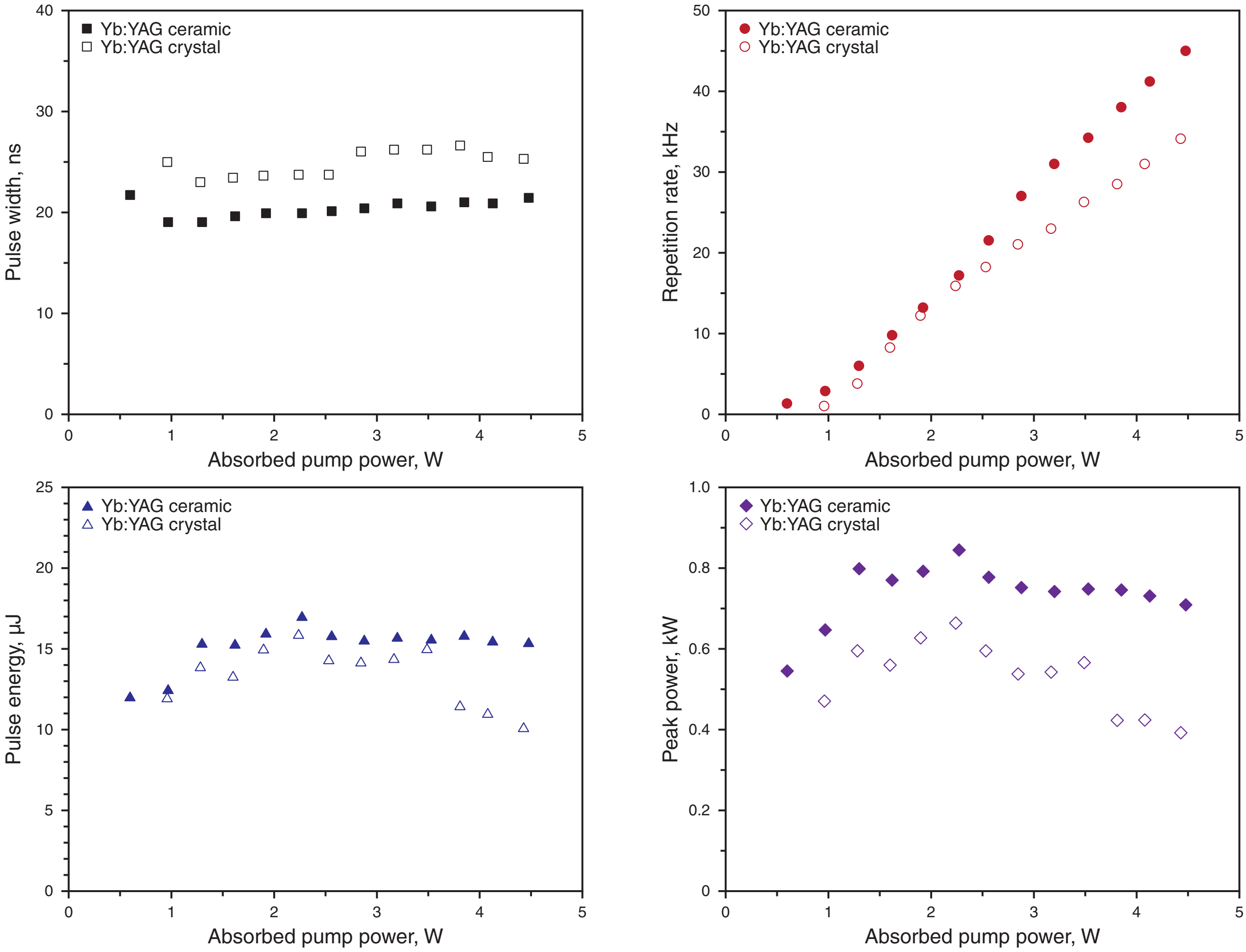

**Figure 5** Pulse width (FWHM), pulse repetition rate, pulse energy, and peak power of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal as a function of the absorbed pump power with $T_{OC} = 20\%$

with $T_{OC} = 20\%$. Two longitudinal modes were obtained when the absorbed pump power was less than 1.3 W. There were three longitudinal modes oscillation when the absorbed pump power was between 1.3 and 3.2 W. Four longitudinal modes were observed when the absorbed pump power is higher than 3.3 W. Five longitudinal modes were obtained when the absorbed pump power reached 3.5 W. Owing to the longitudinal mode hopping and competition, the number of longitudinal mode decreases when the absorbed pump power is higher than 3.8 W. Three longitudinal modes oscillate when the absorbed pump power is 4.48 W. The separation between each longitudinal mode was measured to be about 0.574 nm, much wider (about 74 times of $\Delta\lambda_c$) than the free spectral range $\Delta\lambda_c = 0.0076$ nm in the laser cavity predicted by $\Delta\lambda_c = \lambda^2/2L_c$, [53], where $L_c$ is the optical cavity length and $\lambda$ is laser wavelength. The cause of wide separation between longitudinal modes is attributed to the intracavity tilted etalon effect of the Cr,Yb:YAG thin plate. The potential output longitudinal modes were selected by the combined etalon effect of the 0.5-mm-thick Cr,Yb:YAG and 1-mm-thick Yb:YAG thin plate as an intracavity etalon [17, 53].

Fig. 4 shows some typical examples of the measured output pulse trains of different longitudinal modes oscillation for $T_{OC} = 20\%$ at different absorbed pump powers. The output pulse train looks stable when the laser oscillates at two-longitudinal-mode and three-longitudinal-mode, as shown in Fig. 4a and Fig. 4b. The time interval between pulses decreases with absorbed pump power. The output pulse trains exhibit periodical pulsation when the absorbed pump power is higher than 3.3 W, at these cases, the lasers oscillate in four-longitudinal-mode and five-longitudinal-mode as shown in Fig. 3c and Fig. 3d. The intensity of pulses relative to different longitudinal mode is different from each other, as shown in Fig. 4c and Fig. 4d. Periodical pulsation does not change with the absorbed pump power when the laser oscillates in the same number

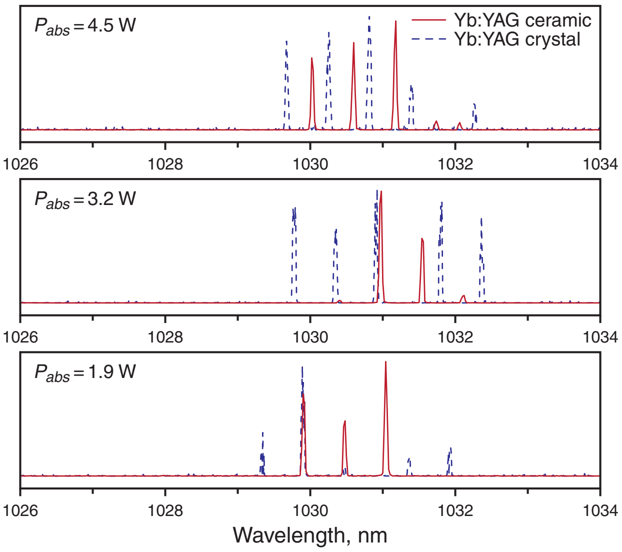

**Figure 6** Comparison of laser emitting spectra of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal under different absorbed pump power levels for $T_{OC} = 30\%$

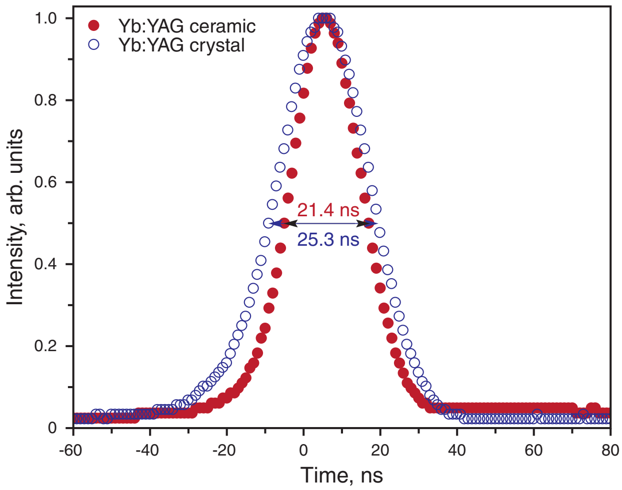

**Figure 7** Oscilloscope trace of laser pulses generated in Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal with $T_{OC} = 20\%$

of the longitudinal modes; the different is the time interval between pulses decreases with absorbed pump power. The same phenomenon was also observed in Cr,Nd:YAG self-Q-switched microchip lasers [54] and passively Q-switched Yb:YAG/Cr$^{4+}$:YAG microchip lasers [55]. Repetition rate jitter between the pulses from different modes for multi-longitudinal-mode oscillations was observed owing to the mode hopping and competition between multi-longitudinal-mode oscillation in Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic. The output pulsation characteristics of this multi-longitudinal-mode oscillation of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic are caused by the cross-saturation mechanism due to the strong spatial hole burning coupling the modes via population gratings and the nonlinear absorption of the Cr$^{4+}$:YAG saturable absorber.

Fig. 5 shows the pulse width, the pulse repetition rate, the pulse width, and the peak power of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic as a function of the absorbed pump power with $T_{OC} = 20\%$, together with the pulse characteristics of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG crystal under the same transmission of the output coupler. The pulse width (full width at half maximum – FWHM) nearly keeps constant at different absorbed pump power levels for Cr,Yb:YAG self-Q-switched lasers by bonding both Yb:YAG ceramic and crystal, the difference is that the pulse width of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic is shorter than that obtained by bonding Yb:YAG crystal. The pulse width is broadened with further increase of the absorbed pump power owing to the strong thermal effect at high pump power levels. The repetition rate increases linearly with absorbed pump power for Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic and crystal. The increase of repetition rate of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic is faster than that by bonding Yb:YAG crystal. This may be caused by the strong multi-longitudinal modes competition induced by the strong thermal effect at high pump power level for Yb:YAG crystal. By bonding Yb:YAG ceramic, the number of longitudinal mode decreases with absorbed pump power at high pump power level (as shown in Fig. 3), the competition between longitudinal modes has less effect of pulse repetition rate than that by bonding Yb:YAG crystal. The pulse energy and peak power obtained in Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic is higher than those obtained in Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG crystal in all the pump power region. Pulse energy and peak power of Cr,Yb:YAG self-Q-switched laser by bonding Yb:AG ceramic increase with the absorbed pump power and tend to be saturated when the absorbed pump power is higher than 1.8 W. The same trend was observed in Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG crystal when the absorbed pump power is lower than 3.5 W. However, the pulse energy and peak power decrease with absorbed pump power when the absorbed pump power is higher than 3.5 W. The pulse width, pulse energy, and peak power are nearly independent of the pump power for different transmission of output couplers. According to the passively Q-switched laser theory [53,56,57], the pulse energy and the pulse width are determined by the initial transmission of saturable absorber and the parameters of the laser cavity, and do not depend on the pump power when the pump power is above the pump power threshold, so is the peak power.

Fig. 6 shows the comparison of laser emitting spectra from Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal for $T_{OC} = 30\%$ under different absorbed pump power levels. Although the laser performance of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic is better than that by bonding Yb:YAG crystal, the laser emitting spectra show that the number of longitudinal modes of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic is less that that obtained by bonding Yb:YAG crystal under different absorbed pump power levels. By bonding Yb:YAG crystal, five longitudinal modes were observed when the absorbed pump power is high than 1.9 W, while only three longitudinal modes were observed by bonding Yb:YAG ceramic. This shows that the mode competition by bonding Yb:YAG ceramic is stronger than that by bonding Yb:YAG crystal at high pump power levels.

Fig. 7 shows the comparison of pulse profiles in Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic and crystal for $T_{OC} = 20\%$ when the absorbed pump power is 4.5 W. The symmetric pulse profile was obtained in both cases, the pulse width of Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic is narrower than that by bonding Yb:YAG crystal. The pulse profile with pulse energy of 15 $\mu$J and pulse width (FWHM) of 21.4 ns from Cr,Yb:YAG self-Q-switched laser by bonding Yb:YAG ceramic was obtained. The corresponding peak power of self-Q-switched lasers is estimated to be 710 W. Self-Q-switched laser pulses with pulse width of 25.3 ns and pulse energy of 10 $\mu$J were obtained in Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG crystal at absorbed pump power of 4.5 W; and corresponding peak power of 392 W was achieved.

## 4. Conclusions

Efficient laser performance of self-Q-switched Cr,Yb:YAG lasers enhanced by bonding Yb:YAG ceramic with a plano-concave resonator have been demonstrated for the first time. Best laser performance of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic was achieved with 20% transmission of output coupler. Maximum output power of 683 mW was obtained when the absorbed pump power of 4.5 W was applied; corresponding optical-to-optical efficiency of 15% was achieved with respect to the absorbed pump power. Slope efficiency of 20% was achieved with $T_{OC} = 20\%$. Laser pulses with pulse energy of 15 $\mu$J, pulse width of 21.4 ns and peak power of 710 W were achieved. Repetition rate of over 45 kHz was obtained. The lasers oscillate in multi-longitudinal-mode and the number of longitudinal modes increases with the pump power. The comparison for the laser performance of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG ceramic and crystal was conducted by varying the transmission of output coupler. For the same $T_{OC}$, the laser performance by bonding Yb:YAG ceramic is better ~~then~~ or comparable to that by bonding Yb:YAG crystal. The performance of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers can be further improved by varying the parameters of Yb:YAG materials and Cr,Yb:YAG crystal.

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