Effect of Polarization States on the Laser Performance of Passively Q-switched Yb:YAG/Cr,Ca:YAG Microchip Lasers

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***Abstract*—The polarization states of passively Q-switched microchip lasers were investigated by adopting different combinations of Yb:YAG, Cr,Ca:YAG crystals and ceramics. The results show that except for the random polarization oscillation of Yb:YAG/Cr,Ca:YAG all-ceramics combination, other three combinations including crystals exhibit linearly polarization. Highly efficient, nearly diffraction-limited beam quality, high peak power, sub-nanosecond passively Q-switched lasers were obtained for all combinations of Yb:YAG, Cr,Ca:YAG ceramics and crystals. The best laser performance was obtained with Yb:YAG/Cr,Ca:YAG crystals combination. The effect of polarization states on the laser performance was also addressed.**

***Index Terms*—Ceramics, Cr,Ca:YAG, crystal, microchip lasers, passively Q-switched, polarization states, Yb:YAG.**

I. INTRODUCTION

COMPACT, high beam quality laser-diode pumped passively Q-switched solid-state lasers with high peak power are potentially used in optical communications, pollution monitoring, nonlinear optics, material processing and medical surgery, and so on [1]. Passively Q-switched solid-state lasers are usually achieved by using neodymium or ytterbium doped crystals as gain media and Cr,Ca:YAG as saturable absorber [2]–[5] or semiconductor saturable absorber mirror (SESAM) [6] as saturable absorber. Compared with SESAM, Cr^{4+} doped bulk crystals as saturable absorber have several advantages, such as high damage threshold, low cost, and simplicity. The output pulse energy from passively Q-switched solid-state lasers is inversely proportional to the emission cross section of gain medium and reflectivity of the output coupler according to the passively Q-switched theory [7]. Besides the broad absorption spectrum [8], longer fluorescence lifetime [9], high quantum efficiency (over 91% with pump wavelength of 941 nm and laser wavelength of 1030 nm) [10] of Yb:YAG gain medium and easy growth of high quality and moderate concentration crystal without concentration quenching [11], smaller emission cross section of Yb:YAG (about one tenth of that for Nd:YAG) [12] is more suitable to obtain high pulse energy output than Nd:YAG in passively Q-switched solid-state lasers. Another interest in Yb:YAG lasers is that the frequency doubled wavelength of 515 nm matches the highest power line of Ar-ion lasers, thereby leading to the possibility of an all solid-state replacement [13]. Linearly polarized laser output was observed in these compact passively Q-switched lasers [14]–[19]. The causes of the linearly polarized output in these passively Q-switched lasers were attributed to the influence of the pump polarization [16], relative orientations of the switch and an intracavity polarizer [18], temperature change induced weak phase anisotropy [19], and the anisotropic nonlinear saturation absorption of Cr,Ca:YAG crystal under high laser intensity [20]. The anisotropic nonlinear absorption of Cr,Ca:YAG crystal induced linearly polarization in passively Q-switched lasers with Cr,Ca:YAG as saturable absorber held until appearing of transparent rare-earths doped YAG laser ceramics [21], [22]. Efficient laser operation in Nd^{3+} : YAG and Yb^{3+} : YAG ceramic lasers has been demonstrated [21]–[23]. Chromium doped YAG ceramic has also been demonstrated to be a saturable absorber for passively Q-switched Nd:YAG and Yb:YAG ceramic lasers [2], [3]. Recently, laser-diode pumped passively Q-switched Yb:YAG/Cr:YAG all-ceramic microchip laser has been demonstrated [3], and pulse energy of 31 μJ and pulsewidth of 380 ps have been achieved with 89% initial transmission of the Cr,Ca:YAG ceramic as saturable absorber and 20% transmission of the output coupler. However, there is coating damage occurrence because of the high energy fluence with low transmission of the output coupler. There are two ways to solve the coating damage problem: one is to improve the coating quality on the gain medium which is costly; the other is to increase the transmission of the output coupler to decrease the intracavity pulse energy fluence. Therefore, 50% transmission of the output coupler was used to balance the output pulse energy and intracavity pulse energy, for this case, the initial transmission of Cr,Ca:YAG can be further decreased to obtain high energy output according to the passively Q-switched solid-state laser theory [7]. The laser performance of passively Q-switched Yb:YAG/Cr,Ca:YAG all-ceramic microchip laser was further improved by using 20% initial

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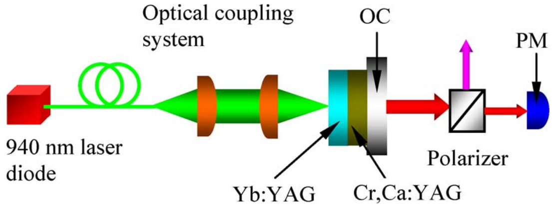


Fig. 1. Schematic diagram for passively Q-switched Yb:YAG microchip lasers with Cr,Ca:YAG as saturable absorber. OC, output coupler; PM, power meter.

TABLE I
POLARIZATION STATES OF PASSIVELY Q-SWITCHED Yb:YAG/Cr,Ca:YAG MICROCHIP LASERS

No.	Combinations	Polarization
C1	Yb:YAG crystal + Cr,Ca:YAG crystal	Linear
C2	Yb:YAG ceramic + Cr,Ca:YAG ceramic	Random
C3	Yb:YAG crystal + Cr,Ca:YAG ceramic	Linear
C4	Yb:YAG ceramic + Cr,Ca:YAG crystal	Linear

transmission of the Cr,Ca:YAG ceramic as saturable absorber and 50% transmission of the output coupler, and no coating damage were observed with high pump power [24]. Highly efficient, sub-nanosecond pulsewidth and high peak power laser operation has been observed in Yb:YAG/Cr^{4+}:YAG composite ceramics [25], [26]. Although linearly polarized states was reported in passively Q-switched Nd:YAG/Cr,Ca:YAG ceramic lasers [27], the extinction ratio was very small. The crystalline-orientation self-selected linearly polarized, continuous-wave operated microchip lasers were demonstrated by adopting [111]-cut Yb:YAG crystal [28] and [100]-cut Nd:YAG crystal [29] as gain medium. Here, we report the polarization states of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers with Yb:YAG crystal or ceramic as gain medium and Cr,Ca:YAG crystal or ceramic as saturable absorber. Based on our previous experiments and results of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers, 20% initial transmission of the saturable absorber and 50% transmission of the output coupler were used in the experiments to compare the polarization states and the effect of the polarization states on the laser performance of these passively Q-switched microchip lasers. Linearly polarized states were observed in Yb:YAG/Cr,Ca:YAG combinations with at least one crystal. For Yb:YAG/Cr,Ca:YAG all-ceramics combination, the laser oscillates at random polarization state. The effect of polarized states of passively Q-switched Yb:YAG/Cr,Ca:YAG lasers on the laser performance was also investigated.

II. EXPERIMENTS

Fig. 1 shows a schematic diagram of experimental setup for passively Q-switched Yb:YAG microchip laser with Cr,Ca:YAG as saturable absorber. Two Yb:YAG samples are used as gain media, one is Yb:YAG ceramic doped with 9.8 at.% Yb, the other is [111]-cut Yb:YAG crystal doped with 10 at.% Yb. The thickness of Yb:YAG samples is 1 mm, and the Yb:YAG samples are polished to plane-parallel. One surface of the gain medium was coated for antireflection at 940 nm and total reflection at 1.03 μm acting as one cavity mirror. The other surface was coated for high transmission at 1.03 μm. Two 1-mm-thick, uncoated Cr,Ca:YAG ceramic and [111]-cut Cr,Ca:YAG crystal with 80% initial transmission, acting as Q-switch, was sandwiched between Yb:YAG sample and a 1.5-mm-thick, plane-parallel fused silica output coupler with 50% transmission. Total cavity length was 2 mm. The initial charge concentration of $CaCO_3$ and Cr_2O_3 in growth of Cr,Ca:YAG crystal and fabrication of Cr,Ca:YAG ceramic are 0.2 at.% and 0.1 at.%, respectively. The absorption center of Cr,Ca:YAG sample centered at 1 μm is also strongly affected by the annealing process and the exact concentration of this absorption center is difficult to determine, the concentration center of this absorption is roughly about 4% of the initial Cr doping concentration [30]. Therefore, the initial transmission of the Cr,Ca:YAG saturable absorber is usually used in comparing the laser performance of passively Q-switched lasers. The initial transmission of Cr,Ca:YAG is governed by the doping concentration and the thickness of the sample, to fully compare laser performance with our previously passively Q-switched Yb:YAG/Cr,Ca:YAG all-ceramic microchip laser and the effect of polarization states on the passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers, 1-mm-thick Cr,Ca:YAG crystal with 80% initial transmission was used in the experiment. It should be noted that the polarization behavior keeps the same if a different modulation depth of Cr,Ca:YAG saturable absorber is used. A high-power fiber-coupled 940 nm laser diode with a core diameter of 100 μm and numerical aperture of 0.22 was used as the pump source. Two lenses of 8-mm focal length were used to focus the pump beam on the Yb:YAG rear surface and to produce a pump light footprint on the Yb:YAG of about 100 μm in diameter. The laser was operated at room temperature. The Q-switched pulse profiles were recorded by using a fiber-coupled InGaAs photodiode with a bandwidth of 16 GHz, and a 7 GHz Tektronix TDS7704B digital phosphor oscilloscope. The laser spectrum was analyzed by using an optical spectrum analyzer. The laser output beam profile was monitored using a CCD camera both in the near-field and the far-field of the output coupler.

III. RESULTS AND DISCUSSION

Four combinations of Yb:YAG and Cr,Ca:YAG were used in the laser experiments to investigate the polarization states of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers: C1, Yb:YAG crystal + Cr,Ca:YAG crystal; C2, Yb:YAG ceramic + Cr,Ca:YAG ceramic; C3, Yb:YAG crystal + Cr,Ca:YAG ceramic; C4, Yb:YAG ceramic + Cr,Ca:YAG crystal. The polarization states of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers with different combinations were investigated by measuring the output power after polarizer. Table I summaries the polarization states observed in passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers with different combinations of Yb:YAG, Cr,Ca:YAG crystals and ceramics. By rotating the combination of Yb:YAG/Cr,Ca:YAG, the polarization states of these lasers do not change, only the polarization directions are changed by arranging Yb:YAG or Cr,Ca:YAG. Rotating any one of sample does not affect the polarization states and no stronger influence on the polarization was observed.

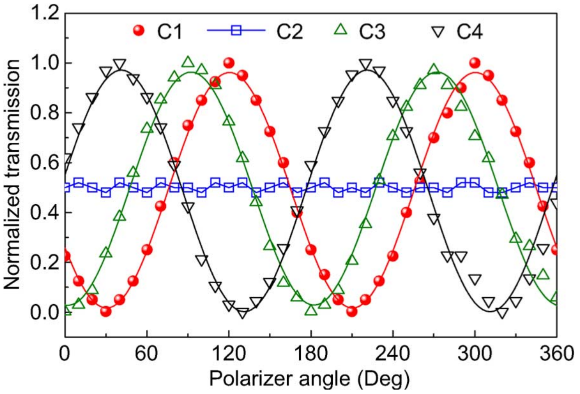


Fig. 2. Polarization states of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers. The solid lines show the sine function fitting of the experimental data.

Fig. 2 shows the typical polarization states of four combinations. Except for the random oscillation of Yb:YAG/Cr,Ca:YAG all-ceramics combination, other three combinations exhibit linearly polarization output. The extinction ratio of the linearly polarization is greater than 300:1. Some differences between the extinction ratios for different linearly polarization were observed. The extinction ratios of three different linearly polarized combinations are in the order of C1 $>$ C4 $>$ C3. The extinction ratios of three different linearly polarized combinations decrease a little with increase of the pump power, we did not observe significant decrease of the extinction ratio at the maximum pump power used here, this shows that the thermal effect under current available pump power is not strong enough to induce sufficient birefringence and depolarization for Yb:YAG crystals and ceramics. However, we did observe the thermal effect under high pump power level for cw Yb:YAG microchip lasers [28], therefore, the thermal effect induced birefringence and depolarization should be considered in high power pumped passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers. The different polarization states between all-ceramics combination and three others are due to the random distribution of nanocrystalline particles in ceramics. To fully understand the nature of polarization states in passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers, we measured the polarization states of Yb:YAG crystals and ceramics by removing Cr,Ca:YAG saturable absorber and found that Yb:YAG crystals oscillate at linearly polarization states selected by the crystalline-orientations in the (111) plane [28] and Yb:YAG ceramic oscillates at unpolarization states. Although there is saturation absorption in Cr,Ca:YAG ceramic, the same as that for Cr,Ca:YAG crystal, owing to the random distribution of Cr,Ca:YAG particles in ceramic, the saturation absorption does not exhibit crystalline-orientation dependent anisotropic properties when the sample is rotated, which is different from the anisotropic saturation absorption of Cr,Ca:YAG crystal when the laser propagate along [111] direction [20]. Therefore, the polarization states in passively Q-switched microchip lasers with Cr,Ca:YAG as saturable absorber are not only determined by the anisotropic saturation absorption of Cr,Ca:YAG saturable absorber, but also determined by the linearly polarized states of Yb:YAG crystals.

The continuous-wave operation of Yb:YAG crystal and ceramic has been investigated previously by using different transmissions of output coupler [22], [31] and found that the laser performance 1-mm-thick Yb:YAG crystal doped with 10 at.% Yb is better than that of 1-mm-thick Yb:YAG ceramic doped with 9.8 at.% Yb. The absorbed pump power thresholds are 0.46 W and 0.54 W for 1-mm-thick Yb:YAG crystal and ceramic, respectively, the slope efficiencies were 49% and 44%, respectively by using 50% transmission of output coupler. The differences of cw laser performance between Yb:YAG crystal and ceramic suggest that the optical quality of ceramic used in the experiments is not as good as that of Yb:YAG crystal, and the slight different doping concentration may be another cause of the difference.

Here we show the effect of different polarization states of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers on the laser performance. Average output power as a function of absorbed pump power for these four combinations of Yb:YAG and Cr,Ca:YAG microchip lasers was shown in Fig. 3. The absorbed pump power thresholds were about 0.53, 0.66, 0.75, and 0.6 W for combinations C1, C2, C3, and C4. The higher pump power threshold of these passively Q-switched lasers was due to the low initial transmission of Cr,Ca:YAG and high transmission of the output coupler used in the experiments. Average output power increases linearly with absorbed pump power for the four combinations, the slope efficiencies with respect to the absorbed pump power were estimated to be about 39%, 36%, 36%, and 29% for the four combinations of C1, C2, C3, and C4, respectively. The best laser performance (low threshold and high slope efficiency) of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers was obtained with C1 combination because of the enhancement of linearly polarized laser operation due to the combination of linearly oscillation of Cr:YAG crystal under high intracavity laser intensity [20] and the crystalline-orientation selected linearly polarized states of Yb:YAG crystal [28]. Maximum average output power of 310 mw was obtained with Yb:YAG/Cr,Ca:YAG all-crystal combination when the absorbed pump power was 1.34 W, corresponding to optical-to-optical efficiency of 23%. The optical-to-optical efficiency is 15% with respect to the incident pump power for C1. The optical-to-optical efficiencies with respect to the incident pump power were measured to be 12, 11 and 11% for C2, C3, and C4, respectively. There is no coating damage occurrence with further increase of the pump power owing to decrease of the intracavity energy fluence by using high transmission output coupler.

Although linearly polarized laser operation was observed in Yb:YAG/Cr,Ca:YAG combinations with at least one crystal, the effect of linearly polarized states on the laser performance was different. The slope efficiency of C4 is lower than that of C3, however the laser threshold of C4 is lower than that of C3 and the average output power is higher than that of C3 for all the available pump power range, as shown in Fig. 3. The contribution of polarization states from Cr,Ca:YAG crystal and Cr,Ca:YAG ceramic is different, when Cr,Ca:YAG crystal is used as saturable absorber, even with Yb:YAG ceramic as gain medium, the laser threshold is low. For all-ceramics combination, C2, although the laser threshold is higher than those of C1 and C4, the slope efficiency is better those of C4 and C3. These results show

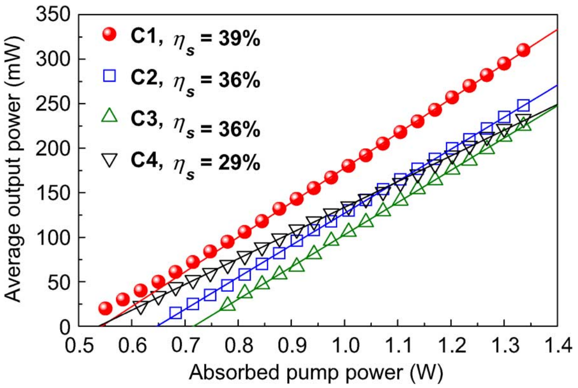
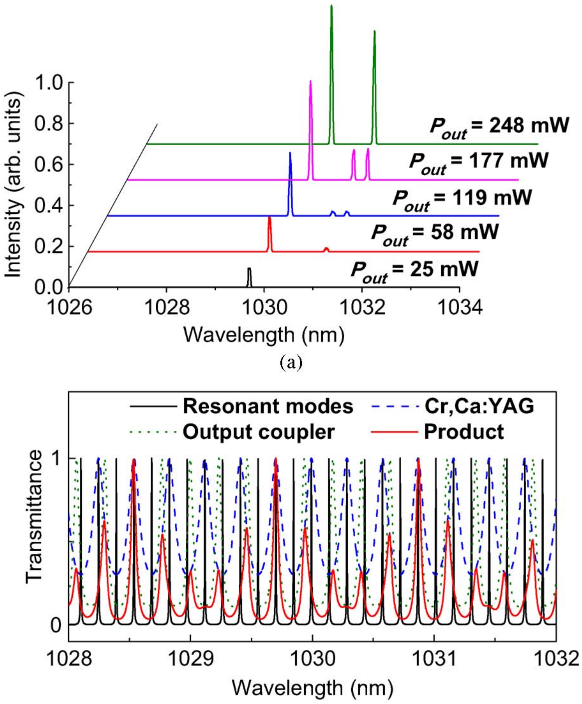


Fig. 3. Average output power as a function of the absorbed pump power for passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers with different combinations of Yb:YAG and Cr,Ca:YAG. The solid lines show the linear fit of the experimental data.



(a)

(b)

Fig. 4. (a) Laser emission spectra under different average output powers in passively Q-switched Yb:YAG/Cr,Ca:YAG all-ceramic microchip laser; (b) transmittance curves of 1-mm-thick Cr,Ca:YAG, 1.5-mm-thick fused silica output coupler, and their transmittance product. Resonant modes are also plotted for illustration.

that the polarized states have great effect on the laser performance. Even with random polarized states of all-ceramics combination, passively Q-switched Yb:YAG/Cr,Ca:YAG laser has nearly the same laser performance as that of all-crystals combination. The discrepancies between all-crystals (C1) and all-ceramics (C2) combinations were caused by the optical quality of Yb:YAG crystal and Yb:YAG ceramic, the laser performance of Yb:YAG crystal is better than its ceramic counterpart. The discrepancies between C3 and C4 were attributed to the linearly polarization, with Cr,Ca:YAG crystal as saturable absorber, the extinction ratio of the polarization is stronger than that of with Cr,Ca:YAG ceramic as saturable absorber, the laser prefers to oscillate more efficiently with orientation selected anisotropic saturbable absorption of Cr,Ca:YAG crystal along $\langle 111 \rangle$ direction under high intracavity intensity [20].

The output beam profile is close to fundamental transverse electro-magnetic mode. Near diffraction-limited output beam quality with $\boldsymbol{M}_x^2$ of 1.05 and $\boldsymbol{M}_y^2$ of 1.04, respectively, was achieved in such compact passively-Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers. The output beam diameter near the output mirror was measured to be 100 μm.

Owing to the broad emission spectrum of the Yb:YAG materials around 1.03 μm (about 10 nm in FWHM), many longitudinal modes can be excited even for a 1-mm-thick Yb:YAG crystal. Microchip cw Yb:YAG lasers operate in a multi-longitudinal-mode over the whole pump power region [22]. However, single-longitudinal-mode oscillation around 1029.7 nm was observed in passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers when the average output power was kept below 50 mW for different Yb:YAG/Cr,Ca:YAG combinations, the same as that for all-ceramics combinations [24]. Above this value, the laser exhibited two-mode oscillation and three-mode oscillation. A typical example of single-longitudinal-mode and multi-longitudinal-mode oscillations of passively Q-switched Yb:YAG/Cr,Ca:YAG all-ceramic microchip laser under different average output power levels is shown in Fig. 4(a). The separation between first and second modes was measured to be 1.16 nm, which is eight times wider than the free spectral range between the longitudinal modes (0.146 nm) in the laser cavity filled with gain medium predicted by [32] $\Delta\lambda_c = \lambda^2/2L_c$, where L_c is the optical length of the resonator and λ is the laser wavelength. The separation between second and third modes was measured to be 0.3 nm, which is twice of that determined by the laser cavity. The potential output longitudinal modes were selected by the combined etalon effect of the 1-mm-thick Cr,Ca:YAG as an intracavity etalon and 1.5-mm-thick fused silica output coupler as a resonant reflector [32]. Fig. 4(b) shows the possible selected modes by the combining effect of 1-mm-thick Cr,Ca:YAG and 1.5-mm-thick fused silica. The resonant modes, eight times of free spectral range (0.146 nm) away from the main mode centered at 1029.7 nm, will oscillate preferably because the wavelengths of these modes are very close to the high transmittance of the combined transmittance product. The resonant mode will oscillate at 1030.87 nm due to the asymmetric gain profile centered at 1029.7 nm of Yb:YAG. At high pump power levels, besides the oscillation of the main mode depleting the inversion population and suppressing the oscillation of the resonant modes close to it, the local temperature rise induced by the pump power will change the transmittance of the etalons. The relative gain and loss for different resonant modes will vary and determine the appearance of the third mode and elimination of the second mode. The linewidth of each mode was less than 0.02 nm, limited by the resolution of optical spectra analyzer. The central wavelength of 1029.7 nm shifts to longer wavelength with pump power, which is caused by the temperature dependent emission spectrum of Yb:YAG crystal [12]. Therefore, stable single-longitudinal-mode oscillation can be maintained by increasing pump beam diameter incident on the laser medium at higher pump power.

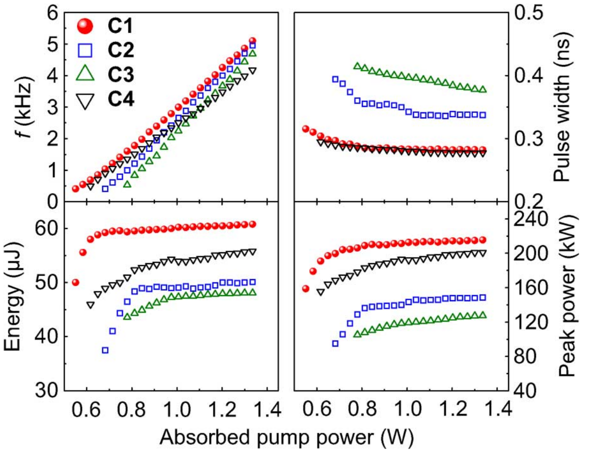


Fig. 5. Pulse characteristics (repetition rate, pulse width, pulse energy and peak power) of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers as a function of absorbed pump power for different combinations of Yb:YAG and Cr,Ca:YAG.

The polarization states of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers have great effect on the characteristics of the output pulses. Fig. 5 shows the pulse characteristics (pulse repetition rate, pulse width, pulse energy and pulse peak power) of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers as a function of absorbed pump power. For all four combinations of Yb:YAG and Cr,Ca:YAG, the repetition rate of passively Q-switched laser increases linearly with the absorbed pump power. Pulse width (FWHM) of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers decreases with absorbed pump power at low pump power levels and tends to keep constant at high pump power levels. The shortest pulsewidth of 277 ps was achieved with C4 combination. Pulse widths for the four combinations are in the order of C4 $<$ C1 $<$ C2 $<$ C3. Pulse energy increases with absorbed pump power and tends to keep constant at high pump power levels. The highest pulse energy was achieved with C1 combination. The pulse energy for the four combinations are in the order of C1 $>$ C4 $>$ C2 $>$ C3. Peak power of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers exhibits the same tendency as those of pulse energy: C1 $>$ C4 $>$ C2 $>$ C3 for the four combinations. Therefore, the overall best laser performance (highest peak power) in passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers achieved by using C1 combination. Linearly polarization operation of passively Q-switched all-crystals lasers is more favorable for laser performance. The combination of Yb:YAG/Cr,Ca:YAG microchip lasers with Cr,Ca:YAG crystal as saturable absorber, C4, has better laser pulse characteristics than those of all-ceramics combination, C2 and combination C3. Although linearly polarized state was achieved in combination C3 with Yb:YAG crystal, the linearly polarized states was attributed to the linearly polarization of Yb:YAG crystal, not from the Cr,Ca:YAG ceramic. The contribution of the linearly polarized state from Yb:YAG crystal in C3 combination is less than that from the nonlinear anisotropic absorption of Cr,Ca:YAG crystal, therefore, therefore, the laser performance of combination C3 is less than those of combination C1 and C4. The effect of depolarization effect on the polarization states observed in Yb:YAG crystal [28] may be another cause to less efficient laser operation in C3 combination at high pump power levels.

IV. CONCLUSION

In conclusion, random polarized oscillation was observed in passively Q-switched Yb:YAG/Cr,Ca:YAG all-ceramic microchip laser while linearly polarized oscillations were observed with at lease one crystal in the Yb:YAG/Cr,Ca:YAG combinations. The polarization states in passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers show that the linearly polarization states in passively Q-switched laser are not only resulted from the anisotropic saturation absorption of Cr,Ca:YAG crystal, but also from linearly polarization states of Yb:YAG crystal. High peak power pulses with sub-nanosecond pulse-width and nearly diffraction-limited beam quality were obtained in these lasers. The best laser performance was achieved by using Yb:YAG crystal as gain medium and Cr,Ca:YAG crystal as saturable absorber because of the enhancement of linearly polarized state due to the crystalline-orientation selected polarized states of Yb:YAG crystal and linearly polarized oscillation of Cr,Ca:YAG crystal under high intracavity laser intensity. Other combinations of Yb:YAG and Cr,Ca:YAG have less efficient linearly polarized laser oscillation and also affect the laser performance of passively Q-switched Yb:YAG/Cr,Ca:YAG microchip lasers.

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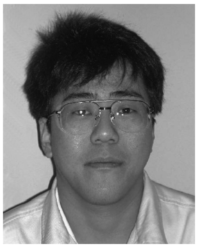

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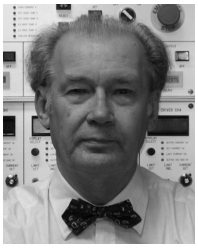

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