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DIODER-PUMPED SELF-Q-SWITCHED Cr^{4+}，Nd^{3+}： YAG LASER WITH AMPLIFIER*

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Abstract： This paper reports results of study on self-Q-switched Cr^{4+}，Nd^{3+}：YAG microchip lasers at 1.064 μm using a quasi-monolithic setup. Pulses with 6 to 60 ns wide（FWHM）and TEM00 mode produced under cw pumping with repetition rates ranging from 1.5 kHz to 23 kHz. Pulsed pumping yielded output pulses with repetition rates from 1Hz to several kHz and excellent pulse stability. A pulsed pumped microchip oscillator and flash lamp pumped amplifiers were used to set up a MOPA（Master Oscillator and Power Amplifier）system generating 225 kW pulses with 8 ns width.

Key words： microchip laser，Cr^{4+}，Nd^{3+}：YAG，MOPA，oscillator，amplifier
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INTRODUCTION

Cr^{4+}：YAG crystals had been widely used as saturable absorbers for flash lamp pumped oscillator and MOPA systems（Shimony et al.，1995，1996，Eichler，1994，1995，Yankov，1994）as well as in diode pumped lasers（Zayhowski et al.，1994）. They presented an easy way to generate passively Q-switched laser pulses. In recent years codoped Cr^{4+}，Nd^{3+}：YAG crystals with combined functions as gain medium and saturable absorber were used as gain media generating self-Q-switched output pulses. Stable output pulse at 1.06 μm and repetition rates of 500 Hz were reported under diode laser pumping（Li et al.，1993），and single longitudinal mode operation was reported soon after Chen et al.（1993）. This paper presents a quasi-monolithic Cr^{4+}，Nd^{3+}：YAG laser generating high repetition rate output pulses pumped with a cw laser diode. Under pulsed pumping，high energy pulses with repetition rates above 1 kHz could be extracted through an amplifier.

EXPERIMENTAL SETUP

Our setup used a 2 mm thick Cr^{4+}，Nd^{3+}：YAG crystal coated on one surface with a dielectric film with high reflection at 1.06 μm and high transmission at 808 nm，and the other surface with an anti-reflection（at 1.06 μm wavelength）coating. Two different 808 nm pump diodes were used：（a）1W cw diode（SDL-2362-P1，100 μm × 1.0 μm）；（b）3W cw diode（SDL-2482-P1，500 μm × 1.0 μm）whose emission was focused by a set of aspherical lenses（Fig.1）. Pumping spots of 50 μm and 150 μm in diameter were obtained respectively.

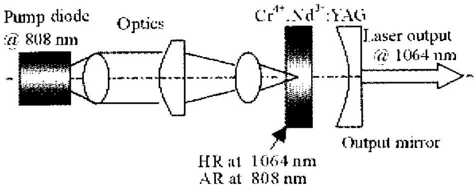

Fig.1　Experimental setup of the diode-pumped self-Q-switched microchip laser

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RESULTS WITH CW PUMPING

Fig.2 shows the average output power and the pulse repetition rate as a function of pump power（1W diode）. When the pump power increased to 400 mW， the saturable absorber bleached and the inversion density reached the threshold. The average output power at the threshold was about 8 mW and increased linearly with the pump power. The pulse repetition rate increased from 5.8 kHz to 23 kHz， and pulse width was nearly independent of the pump power. Using an output mirror with 0.2% transmission， we achieved a minimum repetition rate of 1.5 kHz.

The pulse width increased almost linearly with the cavity length（Fig.3）and the reflectivity of the output coupling mirror.

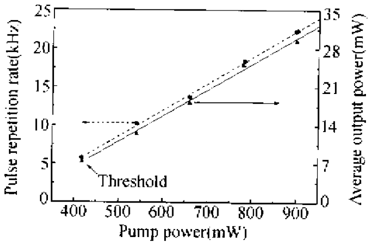

Fig.2 Average output power（solid line）and pulse repetition rate（dotted line）as a function of pump power. A 5 cm concave mirror with 2% transmission was used placed 45 mm behind the end surface of the crystal

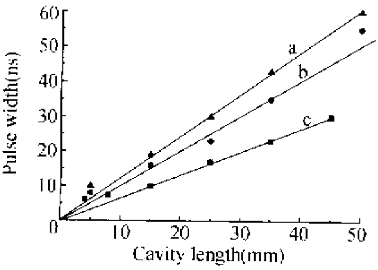

Fig.3 FWHM pulse width as a function of the cavity length

（a） concave output mirror with 0.2% transmission and 75 mm radius of curvature;

（b） concave output mirror with 3% transmission and 75 mm radius of curvature;

（c） plane output mirror with 5% transmission

Fig.4 shows an output pulse train. The pulse to pulse intensity fluctuations were lower than 10%. With the adjustment of the output mirror， the pulse repetition rate and the peak power varied， while the pulse width was almost constant.

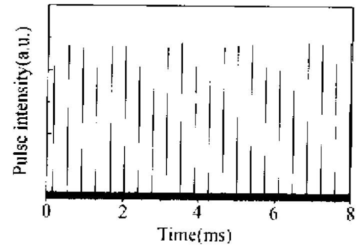

Fig.4 Output pulse train from cw pumped microchip laser（cavity length = 20 mm， pump power = 670 mW，75 mm concave mirror with 3% transmission）

In a self-Q-switched laser， the threshold inversion N_0 is proportional to the total cavity loss δ_i

$$N_0 \propto \delta_i = \delta_{abs} + \delta_{par} + \delta_{out} \qquad (1)$$

where δ_{abs}， δ_{par}， δ_{out} are the loss constants for the round-trip absorption of crystal at low power， intracavity parasitic loss， and the output coupling， respectively.

When the intensity inside the laser cavity is sufficiently high， the absorption of the crystal decreased rapidly to a low level due to the saturation of the absorption. The second threshold inversion of the Q-switched laser was

$$N_{th} \propto \delta_{re} + \delta_{par} + \delta_{out} = \delta_{th} \qquad (2)$$

where， δ_{re} is the round-trip residual loss constant.

The initial inversion ratio r of the Q-switched laser is defined by:

$$r = \frac{N_0}{N_{th}} = \frac{\delta_i}{\delta_{th}} \qquad (3)$$

The pulse width（FWHM: full width at half maximum）is given by（Siegman， 1986）

$$t_p = \frac{r\eta(r)}{r - 1 - \ln r} \cdot \frac{2L}{\delta_{th} c} \qquad (4)$$

where L is the cavity optical length and c is the light velocity in the vacuum； η is the energy extraction efficiency for the conversion of initial stored energy into Q-switched pulse energy. The implicit relation between the initial inversion ratio and the energy extraction efficiency η（Siegman，1986）is

$$r = \frac{1}{\eta(r)}\ln\left(\frac{1}{1-\eta(r)}\right) \tag{5}$$

Eq.（4）shows that the pulse width t_p increases linearly with the cavity optical length L. The slope depends on the initial inversion ratio r and cavity loss constant δ_i which can be obtained using the measured transmission of 94%. This corresponds to an absorption coefficient $\alpha = 0.32$ cm^{-1} similar to that in reference（Zhou et al.，1993）. Then the corresponding absorption loss constant δ_{abs} of 0.13 can be calculated. δ_{out} values are listed in Table 1 for different output mirrors. The rest of the parasitic losses in the resonator could be neglected. Collating Eq.（4）and Eq.（5）with the experimental values of t_p we obtained the extraction efficiency η，and the initial inversion ratio r. With the value of r and δ_i，the residual loss δ_{re} was calculated from Eq.（2）and Eq.（3）. The results are shown in Table 1.

Table 1 Calculated results of η，r and δ_{re}

Number	δ_{out}	η	r	δ_{re}
a	0.002	0.323	1.21	0.108
b	0.03	0.337	1.22	0.102
c	0.05	0.46	1.34	0.87

The results showed that δ_{re} was about 0.1，which meant that the round-trip absorption was only weakly bleached.

RESULTS WITH PULSED PUMPING

In order to control the pulse generation，the crystal was pumped by a pulsed laser diode which resulted in more stable output than under cw pumping（Fig. 5）. The measured intensity fluctuation was lower than 3%. The repetition rate of the Q-switched pulses varied from 1Hz to several kHz.

Under pulsed pumping，the number of output pulse in each pump period depended on the duration of the pump pulse. Fig. 6 shows that single pulse output was realized when the pump period was 115 μs and the pump power was 2.5 W. The pump period for the single pulse output depended on the peak power of the pump pulses. Since the average inversion density would reach threshold earlier at higher pump power，the pump period must be reduced at the same time to get single pulse output，e.g. when the pump power increased to 3W，the pulse duration had to be reduced to 95 μs to achieve single pulse output. On the other hand，with longer pump pulse duration multi-pulses were generated in one pump period，e.g. when the pump duration increased to 200 μs，three pulses with different peak power were obtained（Fig.7）.

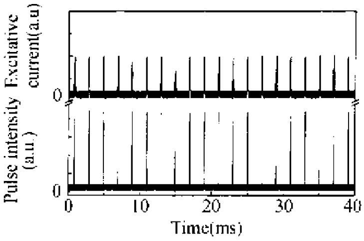

Fig.5 Stable pulse output with pulse pumping（75 mm mirror with 3% transmission，pump power = 900 mW，pump frequency of 500 Hz）

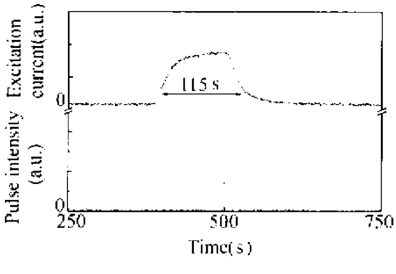

Fig.6 Single pulse output from one pump period（75 mm concave mirror with 3% transmission，pump frequency of 500 Hz）

Fig. 8 shows the average output power at different repetition rates from 300 Hz to 1 kHz. The average output power increased linearly with the repetition rate. Fig. 9 shows the transversal mode structure of the lasing emission measured by a CCD camera. Fig. 10 shows the temporal structure of laser output pulse from the oscillator.

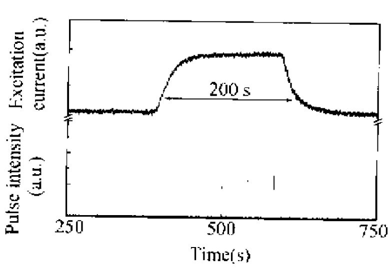

Fig.7 Multi-pulse output from one pump period (75 mm concave mirror with 3% transmission, pump frequency of 500 Hz)

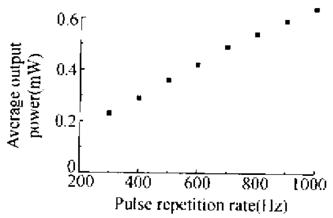

Fig.8 Average output power vs. pulse repetition rate

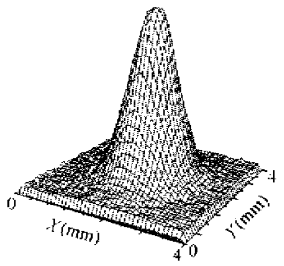

Fig.9 The fundamental mode output from oscillator

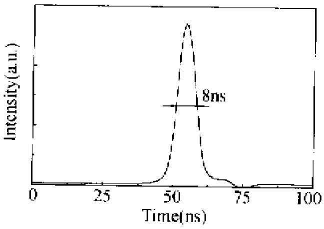

Fig.10 The temporal structure of the laser output pulse from the oscillator

AMPLIFICATION

Although a microchip laser easily generates pulses with several ns width, the peak power of the output pulse is limited. Therefore, amplification is necessary where higher peak power is required.

The emission from a microchip oscillator was amplified by two flash lamp pumped Nd^{3+} : YAG 6 mm diameter 8 cm long rods. Fig. 11 shows the setup of the system. A signal generator SG triggers the diode driver SDL-822 and controls the power driver of the amplifiers.

The peak power of the pulse from the oscillator was about 100 W equivalent to 0.85 μJ pulse energy. After the second amplifier, the peak power increased to 225 kW equivalent to a pulse energy of 1.8 mJ.

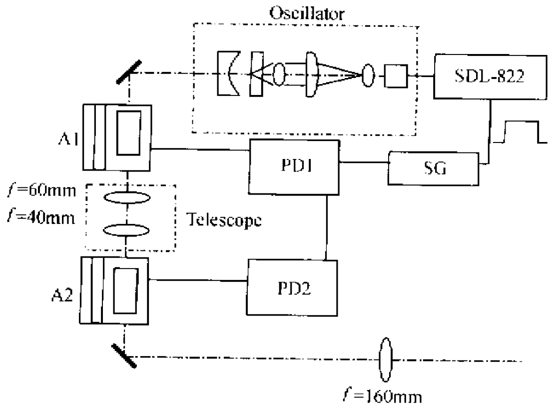

Fig.11 Setup of the master oscillator power amplifier system

A1, A2: amplifiers; SG: signal generator; PD1, PD2: power driver of A1, A2

CONCLUSIONS

In this paper, we report the LD pumped Cr^{4+}, Nd^{3+} : YAG microchip laser under both cw and pulsed pumping. With cw pumping, high repetition rate pulses up to 23 kHz could be generated. The pulse repetition rate increased linearly with the pump power, while the pulse peak power and the pulse width kept constant. A microchip oscillator with controllable repetition rates from 1Hz to several kHz was obtained with pulsed pumping. The amplification of the radiation from this microchip oscillator was achieved with two flash lamp pumped amplifiers. The total output power reached 225 kW.

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