1. INTRODUCTION

The Q-switched nanosecond laser sources near 1.3 μm have wide applications in many fields such as optical fiber communication, micro machining, remote sensing, information storage and so on, so it has attracted much attention in recent years. The Q-switching operation of this kind of laser can be realized by inserting the proper saturable absorbers into the laser resonator oscillating at 1.3 μm. Active Q-switching can be realized by spinning prisms [1], the frustrated total internal reflection (FTIR) Q-switch [2], electro-optical (EO) [3] and acousto-optic (AO) [4] Q-switches. The spinning prisms and FTIR Q-switches have large noise and need repairing usually, while the EO Q-switch needs high voltage applied, so they are gradually replaced by the AO Q-switch in the active Q-switched lasers because of its simplicity. On the other hand, passive Q-switching can be realized with the saturable absorption of saturable absorbers, such as Co:LMA [5–7] and vanadium–doped yttrium aluminium garnet V3+:YAG [8, 9] which can work in the range from 1.05 to 1.45 μm [10, 11]. As for V3+:YAG crystal, there are different peaks observed in the absorption spectrum, which are attributed to two possible co-ordination sites of the V3+ ions: tetrahedral and octahedral. The former one is corresponding to the absorption peak at 1320 nm due to the transition 3A2 → 3T3(3F), which also makes it possible for the passive Q-switching at 1342 nm. The lifetime of the 3T3(3F) level is found to be 22 ± 6 ns [8]. The ground- and excited-state absorption cross sections were calculated to be σgsa = (7.2 ± 2.6) × 10−18 cm2 and σesa = (7.4 ± 2.8) × 10−19 cm2 at 1342 nm, respectively [11]. Up to now, V3+:YAG saturable absorber has been successfully employed in Nd:KGW, Nd:YAG [12], Nd:YAP, or Nd:YVO4 [13] lasers at 1.34 μm, and shown excellent passive Q-switching performance [8, 9, 11].

AO Q-switched lasers can obtain stable pulse train output with high peak power. However, the pulse width of AO Q-switched lasers is usually large. Passively Q-switched lasers with V3+:YAG saturable absorber can generate shorter pulse than AO Q-switched lasers, but the pulse repetition rate is not very stable and the pulse peak power are low. If an AO modulator and a V3+:YAG saturable absorber are simultaneously used in the cavity, known as double Q-switching, it is available to obtain shorter pulse with stable repetition rate and higher pulse peak power. In the doubly Q-switched laser, the AO Q-switch is used to control the pulse repetition rates and allow the laser crystal to store energy to ensure that the population inversion is fully saturated while the V3+:YAG saturable absorber is used to generate short laser pulses through the normal saturable absorption characteristics. In recent years, AO modulator and GaAs coupler have been simultaneously used in solid state lasers to generate shorter pulses with high peak powers and symmetric temporal profiles [14]. Moreover, A–O Q-switched Nd:GdVO4 laser by direct-diode pumping into the emitting level has been reported [15]. However, only a few experimental results were given.

In this paper, by simultaneously using both an AO modulator and a V3+:YAG saturable absorber in the cavity, a diode-pumped doubly Q-switched Nd:GdVO4 laser is presented. The pulse duration is
obviously compressed in contrast to purely AO Q-switched laser. In addition, both the pulse energy and the peak power are higher than that of the passively Q-switched Nd:GdVO$_4$ laser with V$^{3+}$:YAG saturable absorber.

2. EXPERIMENTAL SETUP

The experimental setup is schematically shown in Fig. 1, in which a plane-concave cavity with a length of 8 cm is employed. The pump source was a commercially available fiber coupled diode laser-array (GKD-30FMS) that delivers a maximum output power of 30 W at the center wavelength of 808 nm. The numerical aperture (NA) of the focusing optics is 0.25 and the pump beam is focused into the laser crystal with a spot of 400 $\mu$m in diameter. The input mirror $M_1$ was a concave mirror with curvature radius of 250 mm. Its plane surface was anti-reflection (AR) coated at 808 nm and the concave surface was high-reflection (HR) coated at 1342 nm ($R > 90\% @ 1342$ nm), high-transmission (HT) coated at 808 and 1064 nm ($T > 80\% @ 1064$ nm). The flat mirror $M_2$ was served as an output coupler, high-transmission (HT) coated at 1064 nm and partial-reflection coated at 1342 nm with transmission of 10%. The laser crystal, a $c$-cut Nd:GdVO$_4$ crystal, was 0.52 at % Nd$^{3+}$-doped with dimensions of $3 \times 3 \times 5$ mm$^3$. The gain medium was wrapped with indium foil and held in a copper block cooled by water at a temperature of 20°C; it was placed close to the concave mirror and the distance between them was 8 mm. The QSGSU-6Q acoustic-optic modulator (The 26th Electronics Institute, Chinese Ministry of Information Industry), the effective length and the highest repetition rate of which are 24 mm and 40 kHz, respectively, is placed near V$^{3+}$:YAG wafer. The distance between the back face of AO modulator and $M_2$ was 10 mm. The saturable absorber V$^{3+}$:YAG with dimensions of $8 \times 8 \times 0.5$ mm$^3$ and initial trans-

![Fig. 1. Schematic of the experimental setup.](image)

![Fig. 2. Average output power versus absorbed pump power.](image)

![Fig. 3. Pulse width versus absorbed pump power for passive and AO Q-switching at 10 kHz.](image)

![Fig. 4. Pulse energy versus absorbed pump power for passive and AO Q-switching at 10 kHz.](image)