1. INTRODUCTION

High power passively mode-locked solid-state laser oscillators providing picosecond pulses at several to hundred megahertz repetition rates are interesting in many applications, such as nonlinear frequency conversion and quasi-CW UV sources for laser direct imaging in the printed circuit industry. To transfer picosecond technology to industrial applications, laser sources of high average power through master oscillator power amplifier (MOPA) system with repetition rate in the megahertz range are essential. An 888-nm diode-end-pumped Nd:YVO₄ oscillator providing 56 W average output power at 110 MHz repetition rate with pulse width of 33 ps has been reported by McDonagh et al., and the output power was further scaled to 111 W using a power amplifier [1]. But Nd:YVO₄ crystal is difficult to grow to big size, and it has a weak thermal conductivity. At present, the maximum TEM₀₀ power output of Nd:YVO₄ laser is just 165 W to the best of our knowledge [2]. Thus, the output power of Nd:YVO₄ is difficult to be scaled to higher level such as kilowatt by using the MOPA system as in [1]. Another Nd-doped crystal Nd:YAG has a much larger thermal conductivity compared with Nd:YVO₄, and large-size Nd:YAG crystal is available. Therefore, the Nd:YAG crystal may be a better choice for high power picosecond laser sources. Lasers based on Nd:YAG crystal have been widely investigated for CW or pulsed operation [3–6]. For high-power picosecond light sources using Nd:YAG crystals, an MOPA system providing 92.7 W output power with repetition rate of 73.3 MHz and the pulse width of 26.5 ps has been reported by Peng et al., in which a passively mode-locked Nd:YVO₄ oscillator was amplified by two diode-end-pumped Nd:YVO₄ amplifiers and then by four diode-side-pumped Nd:YAG rod laser heads amplifiers, but the extracted efficiency for the pump power is only about 6% due to the difference of the laser emission wavelengths between Nd:YAG and Nd:YVO₄ [5]; an 808-nm diode-side-pumped passively mode-locked Nd:YAG oscillator has also been demonstrated by Spühler et al., providing 27 W output power at 55 MHz repetition rate with 19 ps pulse width, but the laser system was very complicated requiring three pump heads and exhibited a limited optical-optical conversion efficiency of only 20% [6].

High output power from an end-pumped laser is usually limited by thermal effects. One way to reduce thermal effects of the laser crystal is to adopt composite crystals combining doped and undoped components, by which the undoped section serves as a heat sink for the pumping surface [7–9]. In Nd-doped lasers, another method is to use direct pumping scheme, which reduces the quantum defect between the laser and pump wavelengths, compared to traditional 808 nm pumping. In recent years, studies have shown that 879 or 880 nm diode direct pumping is an efficient way to reduce thermal loading in Nd:YVO₄ lasers [8, 10]. While in Nd:YAG lasers, 885 nm direct pumping scheme in stead of traditional 808 nm diode pumping leads to reduced thermal effects and higher optical-optical conversion efficiency [11–14], all contributing to achieve high output power. At present, 885-nm diode-pumped lasers have been reported for continuous wave (CW) operation [12, 14], but no passively mode-locked Nd:YAG laser has been reported under 885 nm diode direct pumping.
In this paper, a high-efficiency, high-power passively mode-locked Nd:YAG oscillator under 885 nm laser diode (LD) directly pumping was reported for the first time with a semiconductor saturable absorber mirror (SESAM). At the absorbed pump power of 38 W, a maximum average output power of 17 W at 80 MHz repetition rate with 39 ps pulse width was obtained with a diffraction-limited beam profile ($M^2 = 1.1$). The optical-optical conversion efficiency was up to 44% to the absorbed pump power, corresponding to the slope efficiency of 69%.

2. EXPERIMENT SETUP

Figure 1 is the schematic illustration of configuration of the laser setup. In the setup, to reduce the thermal effects, a $\varnothing 3 \times 40$ mm composite Nd:YAG rod crystal consisting of one 5-mm undoped end cap YAG and a 35-mm 0.9 at % Nd-doped section was used as the laser medium, and an 885 nm fiber-coupled LD (DILAS) was used as the pump source. The fiber has a core diameter of 400 μm and a numerical aperture of 0.22. The pump radiation from the fiber was focused into the long Nd:YAG crystal by some coupling lenses with 1:4 magnification, providing an almost collimated pump beam along the whole length of the crystal. Both sides of the Nd:YAG crystal were AR-coated at 1064 and 885 nm to reduce the optical loss and avoid potential etalon effect. To remove the generated heat, the Nd:YAG crystal was water-cooled and the temperature of water was set at 25°C during the operation. The cavity was a Z-folded resonator with three mirrors and a SESAM. $M_1$ was a flat-wedged mirror used as the output coupler with transmittance of 20% at 1064 nm. The input and folding mirror $M_2$ was a flat mirror with high-reflectance coating at 1064 nm and anti-reflectance coating at 885 nm. $M_3$ was a highly reflective mirror at 1064 nm ($R > 99.8\%$) and the radius of curvature of $M_3$ was 500 mm. The total cavity length was 1875 mm for the repetition rate of 80 MHz, and the arm lengths are 300, 1162, and 340 mm for $L_1$, $L_2$, and $L_3$, respectively. Because $M_3$ was a spherical mirror, it would cause astigmatism that strongly affected the operation of the mode-locked laser. Then the folded angle between $L_1$ and $L_2$ was kept to no more than 8°, and the laser mode was calculated to be about 450–470 μm in radius at the center of the Nd:YAG laser crystal during the experiment.

The modulation depth, non-saturable loss, and absorption recovery time of the SESAM are important in the design of a passively mode-locked laser. We can get the equation below [15]

$$F_{\text{sat, A}} = \frac{F_{\text{sat, L}} A_{\text{eff, L}} \Delta R}{\beta^2 A_{\text{eff, A}}}$$

where $F_{\text{sat, A}}$ denotes absorber saturation fluence of the saturable absorber, $F_{\text{sat, L}}$ represents saturation fluence of the gain medium, $A_{\text{eff, L}}$ is the effective mode area inside the gain medium, $\Delta R$ is the maximum modula-