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# High-Efficiency Ho:YAP Pulse Laser Pumped at 1989 nm

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**Abstract:** A Tm:YAP laser with an output wavelength of 1989 nm was selected for the first time as the pump source of a Q-switched Ho:YAP laser. When the absorbed power was 30 W, an average power of 18.02 W with the pulse width of 104.2 ns acousto-optic (AO) Q-switched Ho:YAP laser was obtained at a repetition frequency of 10 kHz. The slope efficiency was 70.11%, and the optical-optical conversion efficiency was 43.03%. The output center wavelength was 2129.22 nm with the line width of 0.74 nm.

**Keywords:** 1989 nm; Ho:YAP; AO Q-switched laser



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## 1. Introduction

2 μm holmium ($Ho^{3+}$) doped solid-state lasers have important application prospects in the fields of laser ranging, laser medical treatment, environmental monitoring, and optical communication due to its near-infrared window and safety to the human eye [1–8]. In addition, 2 μm $Ho^{3+}$ doped lasers were considered as good pump sources for mid-far infrared optical parametric oscillator (OPO) [9]. Compared with Ho:YAG, Ho:YLF and Ho:$GdVO_4$ crystals, Ho:YAP crystal has obvious advantages, such as wide absorption line, large absorption cross-section, anisotropy, short growth period, the output power was not easy to saturate, and so on. There are many absorption peaks in Ho:YAP crystal at 1.9 μm. For an a-cut Ho:YAP crystal, the absorption peaks included 1872 nm, 1907 nm, 1931 nm, 1970 nm and 2045 nm. For a b-cut Ho:YAP crystal, the absorption peaks included 1884 nm, 1923 nm, 1946 nm, 1984 nm, 2023 nm and 2059 nm [10]. For a c-cut Ho:YAP crystal, the absorption peaks included 1915, 1941, 1980, and 1996 nm [11]. A maximum absorption peak for a-, b-, and c-cut Ho:YAP crystals was about 1976 nm [12].

In recent years, there are many reports on Ho:YAP lasers. In 2009, a Tm:YLF laser with the output wavelength of 1900 nm was used to pump the continuous wave Ho:YAP laser, was reported by Duan et al. [13]. The output power was 10.2 W, with the slope efficiencies of 64.0%, the optical-optical conversion efficiencies of 52.6%, and the output wavelength of 2118 nm. In 2011, a Tm:YLF laser with output wavelength of 1910 nm was used to pump the Ho:YAP (b-cut) Q-switched laser at room temperature, was reported by Yang et al. [14]. When the Q-switched repetition frequency was 5 kHz, the output power was 18.1 W, the slope efficiencies was 45.9%, the optical-optical conversion efficiencies was 36.5%, and the output wavelength was 2118 nm. In 2012, the theoretical and experimental analysis of a Ho:YAP (a-cut) crystal of 2 μm laser was reported by Yang et al. [15]. The pump wavelength was 1900 nm. The CW output power was 15.6 W. The slope efficiencies was 63.7%, the optical-optical conversion efficiencies was 54.5%, and the output wavelength was 2118 nm. In 2012, a Tm:YLF laser with an output wavelength of 1910 nm was used to pump the Q-switched Ho:YAP (a-cut) ring laser, was reported by Dai et al. [16]. When the Q-switched repetition frequency was 1 kHz, the output power of 10.17 W was obtained, the slope efficiencies was 60%, the optical-optical conversion efficiencies was 29.5%, and the output wavelength was 2119 nm. In 2014, a Tm fiber laser with the output wavelength of 1910 nm was used to pump the Q-switched Ho:YAP (a-cut) laser, was reported by Wang et al. [17]. When the Q-switched repetition was 10 kHz, the output power of 11.0 W was obtained with the slope efficiencies of 62.1%, the optical-optical conversion efficiencies of 26.3%, and the output wavelength of 2118.0 nm. In 2014, Tm:YLF laser with an output wavelength of 1910 nm was used to pump Ho:YAP (a-cut) Q-switched laser, was reported by Duan et al. [18]. When the Q-switched repetition frequency was 10 kHz, 17.2 W output power was obtained, the slope efficiencies was 63.2%, the optical-optical conversion efficiencies was 29%, and the output wavelength was 2118 nm. In 2016, a Tm fiber laser with the output wavelength of 1910 nm was used to pump a mode-locked Ho:YAP laser, was reported by Duan et al. [19]. The output power of 2.87 W was obtained, with a slope efficiency of 15%, an optical–optical conversion efficiency of 11.9%, and an output wavelength of 2118 nm. In 2017, a Tm fiber laser with an output wavelength of 1941 nm was used to pump a Ho:YAP (c-cut) laser, as reported by Ting et al. [11]. The output power of 29 W was obtained with the slope efficiency of 42.8%, the optical–optical conversion efficiency of 60.67%, and the output wavelength of 2118 nm. In 2018, a Tm fiber laser with an output wavelength of 1910 nm was used to pump a Ho:YAP (b-cut) laser, as reported by Duan et al. [20]. The output power was 10.5 W, the slope efficiency was 53.2%, the optical–optical conversion efficiency was 41%, and the output wavelength was 2115 nm. In 2020, a Tm:YAP laser with output wavelength of 1940 nm was used to pump the electro-optic Q-switched Ho:YAP (a-cut) laser reported by Lei et al. [21]. When the repetition frequency was 4 kHz, the output power was 6.5 W, the slope efficiency was 50.6%, the optical-to-optical conversion efficiency was 28%, and the output wavelength was 2118 nm.

As mentioned above, Tm-doped solid-state lasers or Tm fiber lasers with output wavelength of 1900 nm, 1910 nm, or 1940 nm are often used as the pumping sources of Ho:YAP lasers. Although there was no pump source whose wavelength matches the strongest absorption peak of Ho:YAP crystal, the slope efficiency of Ho:YAP lasers was quite high under all kinds of situations, such as continuous or Q-switch or mode-locked operation, which means that the Ho:YAP crystal was one of the most promising $Ho^{3+}$ doped lasers.

Under the premise of ensuring that the Ho:YAP crystal absorbs enough pumping power, the closer the wavelength of output laser and pumping laser, the smaller the quantum loss. However, there is not report on a Ho:YAP laser pumped by a 1989 nm laser, to our best knowledge.

In this paper, a Tm:YAP laser with the output wavelength of 1989 nm was selected for the first time as the pump source of Q-switched Ho:YAP laser. When the absorbed power was 30 W, the output power of acousto-optic (AO) Q-switched Ho:YAP laser was 18.02 W, and the pulse width was 104.2 ns at repetition frequency of 10 kHz. The corresponding slope efficiency was 70.11%, and the optical-optical conversion efficiency was 43.03%. The output center wavelength was 2129.22 nm.

## 2. Materials and Methods

The experimental configuration was shown in Figure 1.

To achieve high output power of Q-switched Ho:YAP laser, four semiconductor lasers (Type: SHCC-FCP-60-200-795-S, Shanghai Chuchuang Optical Machinery Technology Co., Ltd., Shanghai, China) with a central wavelength of 795 nm were used as pumping sources of Tm:YAP laser.

Two Tm:YAP crystals with the same parameter were used in the experiment. The Tm:YAP crystal had a cross-section size of 4 mm × 4 mm, a length of 12 mm, and $Tm^{3+}$ doping concentration of 3 at.%. Both ends of the crystal were coated with high transmissivity at 1989 nm and 795 nm. The crystal was wrapped in thick indium foil with the thickness of 0.1 mm and placed in a copper heat sink. The heat sink was cooled by water, which was kept at 18 °C.

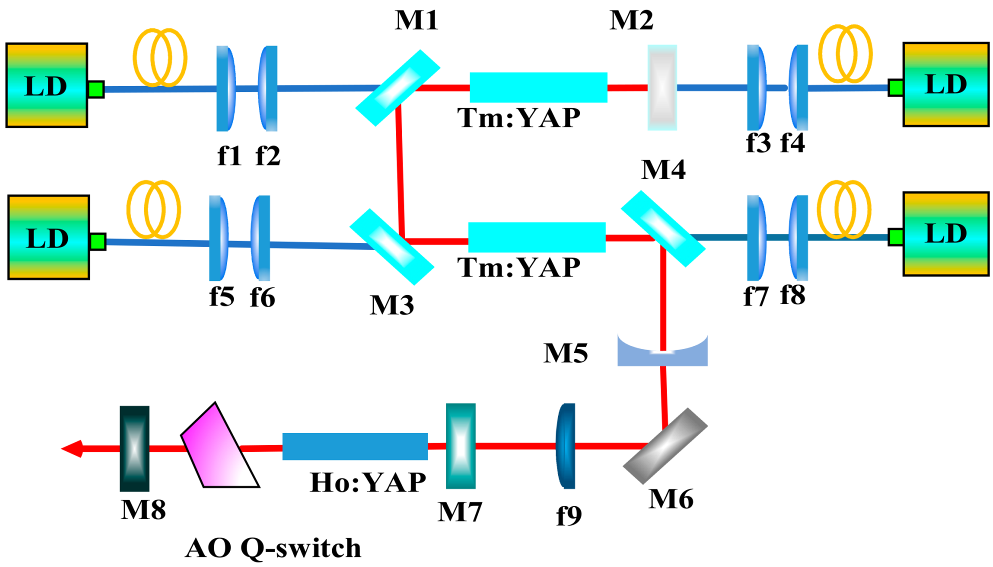


**Figure 1.** Acousto-optic Q-switched Ho:YAP laser pumped by 1989 nm laser.

The output power of Tm:YAP laser was improved by using a laser diode (LD) double-ended pump structure. The cavity was formed by flat mirrors M1, M2, M3, M4, and a concave mirror M5. M1, M3 and M4 were 45° mirrors coated with high transmissivity at 795 nm and high reflectivity at 1989 nm. M2 was a 0° mirror coated with high transmissivity at 795 nm and high reflection at 1989 nm. Curvature radius of the output coupler M5 was 300 mm and coated with transmissivity of 10% at 1989 nm.

Good mode matching between the pumping beam and oscillating beam of the Tm:YAP laser was achieved by adjusting the focus coupling mirrors, f1 = f4 = f5 = f8 = 25 mm, f2 = f3 = f6 = f7 = 50 mm. The focus lenses were anti-reflection coated at 795 nm. We measured the pump power before the lenses and after M1, M2, M3 and M4, and we calculated the pump transmission to be about 90%.

The resonator of Ho:YAP was a straight cavity composed of M7 and M8. M7 was coated with high transmissivity at 1989 nm and high reflectivity at 2118 nm. Curvature radius of the output coupler M8 was 100 mm and coated with high transmissivity at 1989 nm and transmissivity of 20% at 2118 nm. The cavity length of Ho:YAP was 70 mm.

The size of Ho:YAP crystal was 4 mm × 4 mm × 25 mm, and the $Ho^{3+}$ doped concentration was 0.8 at. %. Both ends of the crystal were coated with high transmissivity at 1989 nm and 2118 nm. The crystal was wrapped in thick indium foil with the thickness of 0.1 mm and placed in a copper heat sink. The heat sink was cooled by water, which was kept at 18 °C.

A quartz acousto-optic Q-switch (QS041-10M-HI8 and the drive model MQH041-100DM-A05, Gooch&Housego Co., Ltd, Ilminster, Somerset, UK) with a length of 46 mm and aperture of 2.0 mm was employed for Q-switching operation. Both ends of the Q-switch crystal were coated with high transmissivity at 2118 nm. The radio frequency was 40.68 MHz, and the maximum radio frequency power was 50 W. The threshold of damage was larger than 500 MW/cm$^2$. The AO Q-switch crystal was cooled by a water cooler at 18 °C.

In order to facilitate the adjustment and realize the good mode matching between the pump light and the oscillating light, plat mirror M6 and focus lenses f9 and f10 were used. M6 was a 45° full mirror coated with high-reflection at 1989 nm. The focus lens f9 = 50 mm was anti-reflection (AR) coated at 1989 nm.

## 3. Results and Discussion

The absorptance of Tm:YAP crystal to pump light was 92%. The output power of Tm:YAP laser was measured with the power meter F150A (OPHIR, Jerusalem, Israel), as shown in Figure 2. The output power of the laser varied linearly with the absorbed power. The threshold power of the laser was 11 W. The maximum output power of the Tm:YAP laser was 50 W, and the slope efficiency was 41.32%. The central wavelength at the maximum output power was 1989.01 nm, which was measured using the spectrometer (AQ6370 of Yokogawa, Musashino, Tokyo, Japan), as shown in Figure 3.

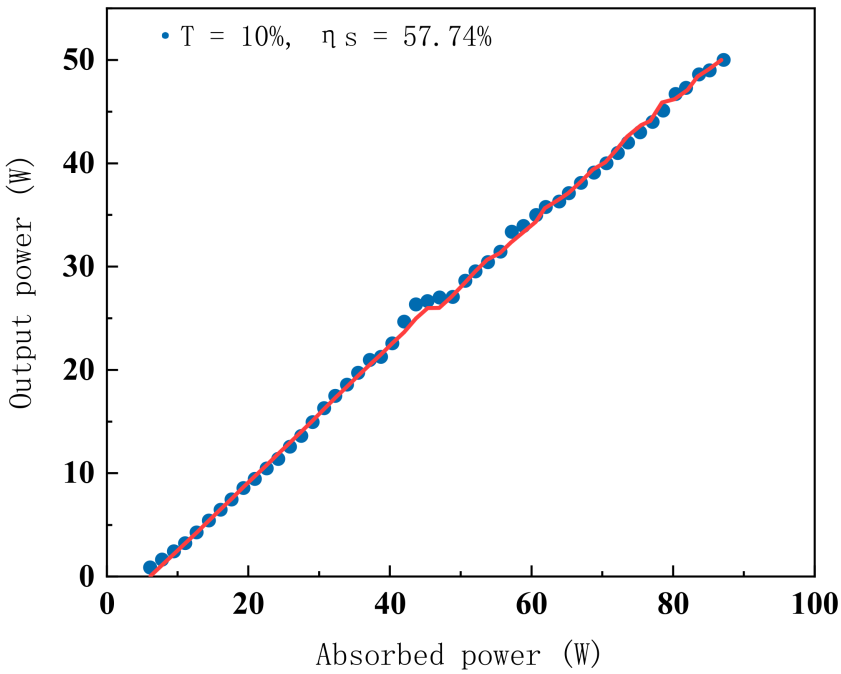


**Figure 2.** Output power versus absorbed power of Tm:YAP laser.

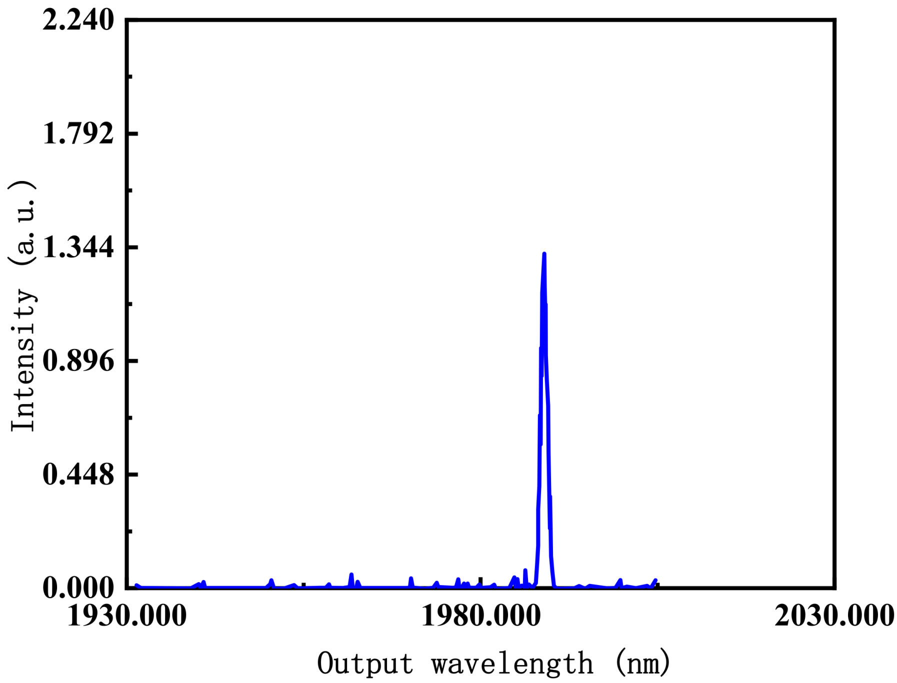


**Figure 3.** Output spectrum of Tm:YAP laser.

The central wavelengths of Tm:YAP laser versus output power were shown in Figure 4. When the output power of continuous Tm:YAP laser varied from 0.5 W to 50 W, the center wavelength of the Tm:YAP laser remained between 1986.00 nm and 1990.00 nm. The fluctuation of the center wavelength was affected by the accuracy of temperature control of the Tm:YAP crystal. However, the output wavelength of the Tm:YAP laser was always in the absorption line width of the Ho:YAP crystal, which means that it can be used as the pump source of the Ho:YAP laser.

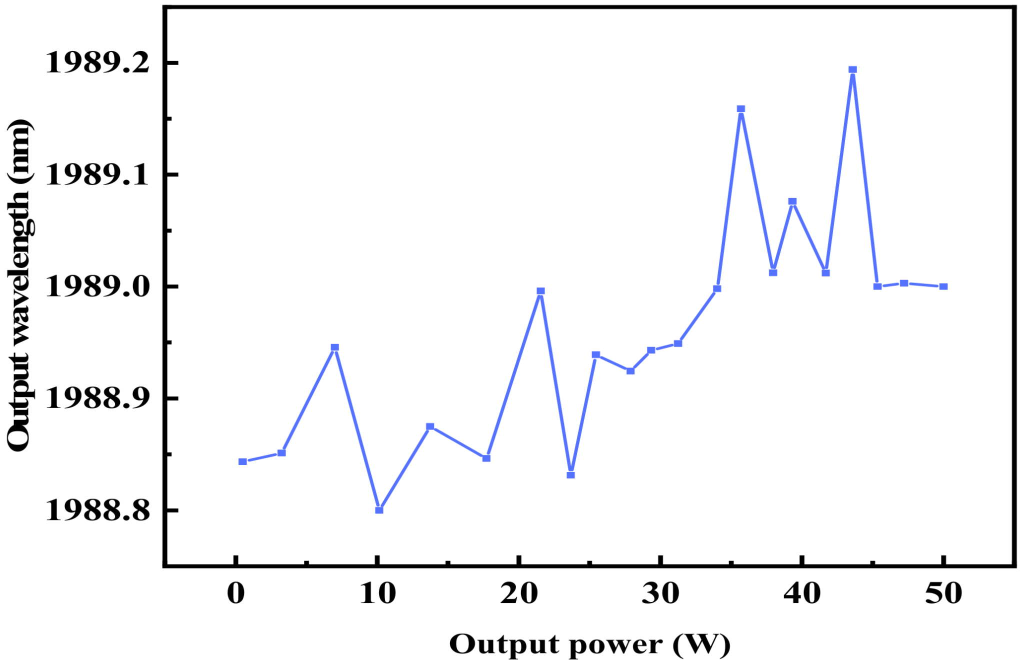


**Figure 4.** Output wavelength of Tm:YAP laser versus output power.

With Tm:YAP laser as the pump source with the maximum output power of 50 W, the experimental study of acousto-optic Q-switched Ho:YAP laser was carried out. The average power of the laser output was measured by a power meter (30A-BB-18, OPHIR, Jerusalem, Israel), and the pulse width of the laser output was measured by an oscilloscope (DPO3054, Tektronix, Beaverton, Oregon, U.S.) and a pulse width detector (PCI-3TE-12, VIGO System S.A., Warsaw, Poland).

As shown in Figure 5, the average output powers of an AO Q-switched Ho:YAP laser versus pump power were achieved under repetition frequency of 1 kHz, 5 kHz and 10 kHz. At pump power of 50 W, the maximum average output powers of AO Q-switched Ho:YAP laser were 14.2, 15.84, and 18.02 W, with the slope efficiencies of 55.25, 61.66, and 70.11%, respectively. The output pulse width of the Q-switched Ho:YAP laser versus the pump power was achieved under different repetition frequencies, as shown in Figure 6. At absorbed power of 30 W, the narrowest output pulse widths were 101.7 ns, 103.1 ns and 104.2 ns under repetition frequency of 1 kHz, 5 kHz, and 10 kHz, respectively.

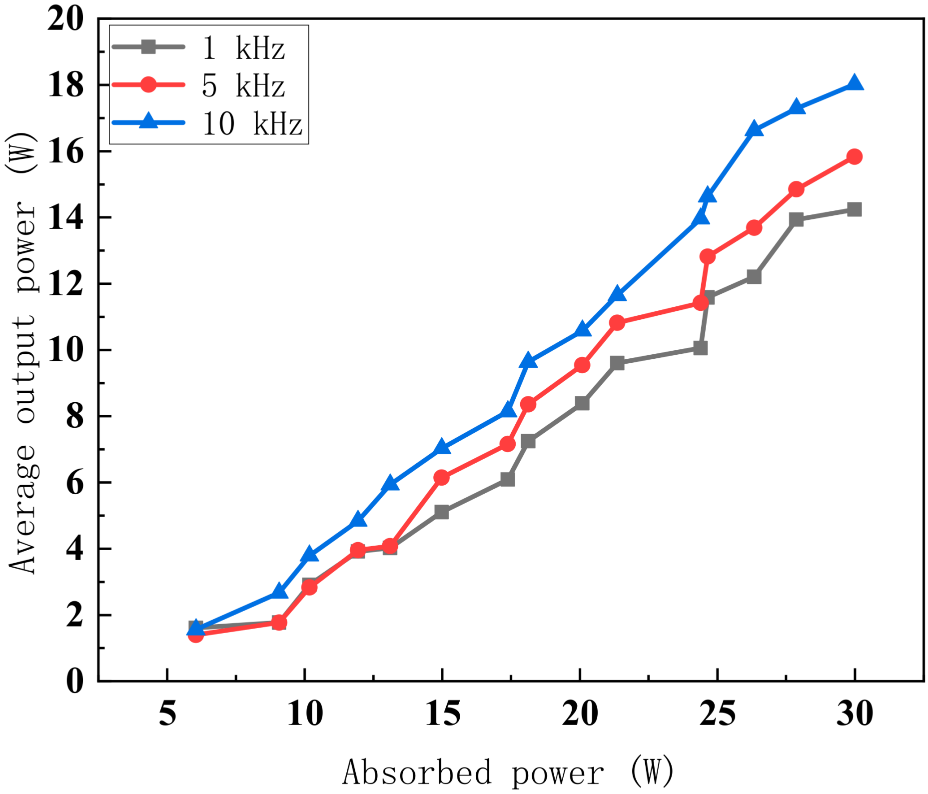


**Figure 5.** Average output power of Q-switched Ho:YAP laser versus absorbed power.

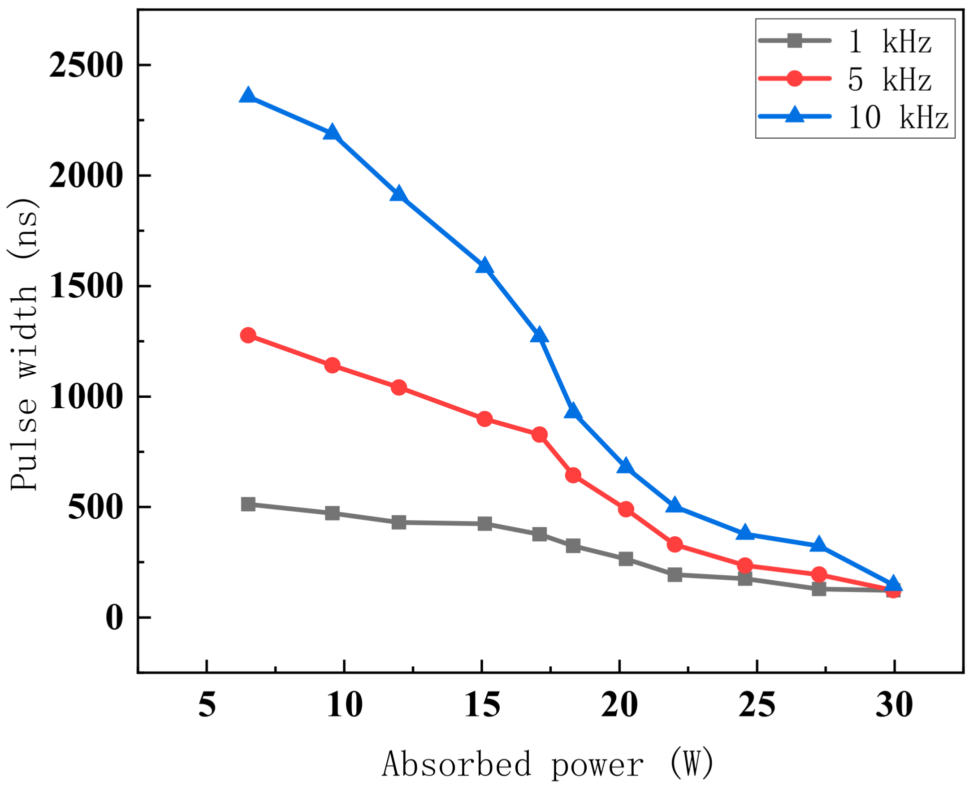


**Figure 6.** Output pulse width of Q-switched Ho:YAP laser versus absorbed power.

The central wavelength of the AO Q-switched Ho:YAP laser was measured using the spectrometer (AQ6370, Yokogawa, Musashino, Tokyo, Japan). The central wavelengths at the maximum output average power were 2129.29 nm, 2129.47 nm and 2129.22 nm, with output linewidths of 0.77 nm, 0.75 nm and 0.74 nm under repetition frequency of 1 kHz, 5 kHz and 10 kHz, respectively.

Figure 7 showed the output spectrum of a Q-switched Ho:YAP laser at an output average power of 18.02 W and repetition frequency of 10 kHz. While, Figure 8 gave the output width of Q-switched Ho:YAP laser under the same condition.

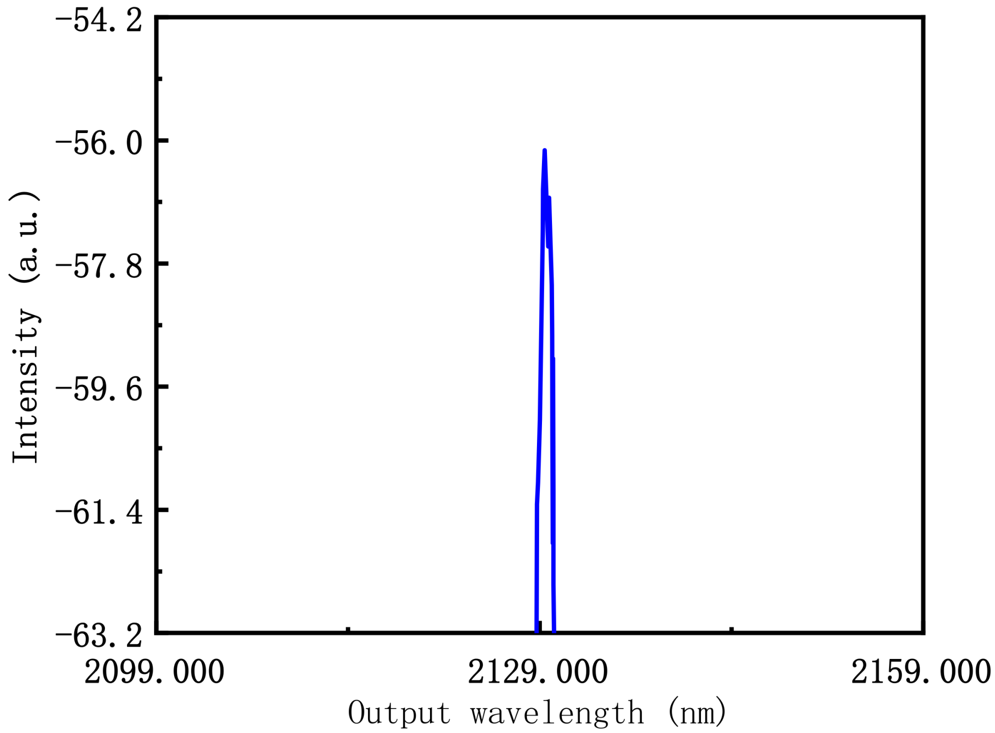


**Figure 7.** Output spectrum of AO Q-switched Ho:YAP laser.

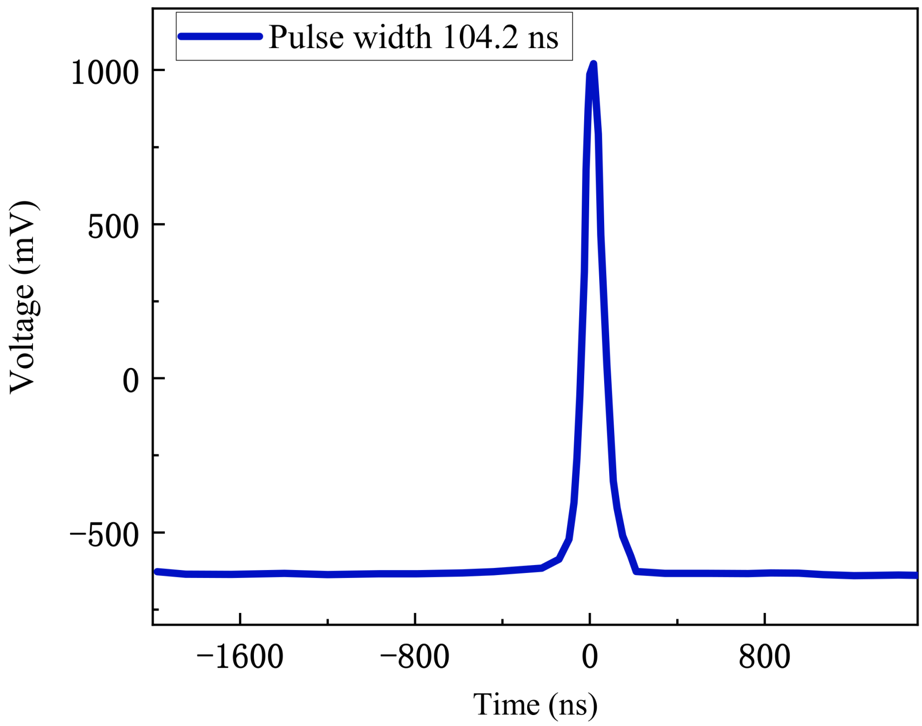


**Figure 8.** Output pulse width of AO Q-Switched Ho:YAP laser.

## 4. Conclusions

We demonstrated an AO Q-switched Ho:YAP laser pumped by the 1989 nm laser for the first time. Under the pump power of 50 W, at a PRF of 1 kHz, the average output power of 14.2 W Ho:YAP laser was obtained, with the slope efficiency of 55.25%, the pulse width of 101.7 ns, and the central wavelength of 2129.29 nm. At a PRF of 5 kHz, the average output power of 15.84 W laser was obtained, with the slope efficiency of 61.66%, the pulse width of 103.1 ns, and the central wavelength of 2129.47 nm. At a PRF of 10 kHz, the average output power of 18.02 W laser was obtained, with the slope efficiency of 70.11%, the pulse width of 104.2 ns, and the central wavelength of 2129.22 nm.

**Author Contributions:** Conceptualization, C.N., Y.W. and C.W.; methodology, T.D. and C.N.; software, C.N., Y.W. and L.Z.; validation, C.N. and Y.W.; formal analysis, X.C. and L.Z.; investigation, Y.J., C.N., L.Z. and X.C.; resources, C.W. and T.D.; data curation, Y.W., Y.J. and C.N.; writing—original draft preparation, C.N.; writing—review and editing, C.W. and Y.W.; visualization, C.N.; supervision, T.D.; project administration, C.W.; funding acquisition, C.W. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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