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Realization of a continuous-wave single-frequency tunable Nd:CYA laser

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We demonstrate an all-solid-state continuous-wave (CW) single-frequency tunable 1.08 μm laser, which is realized by employing a disordered laser medium Nd:$CaYAlO_4$ (Nd:CYA) crystal. The maximal output power of single-frequency 1.08 μm laser is 1 W. By rotating the incident angle of the intracavity etalon (IE), the maximal tuning range of 183.71 GHz is achieved. After the IE is locked to the oscillating longitudinal mode of the laser, the continuous tuning range of 60.72 GHz for 1.08 μm laser is achieved by scanning the cavity length. To the best of our knowledge, this is the first demonstration of a CW single-frequency widely tunable 1.08 μm laser based on Nd:CYA crystal.

Keywords: all-solid state laser; continuous wave; continuous tuning; Nd:$CaYAlO_4$ crystal.

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1. Introduction

All-solid-state continuous-wave (CW) single-frequency lasers have been established as efficient devices, capable of generating high stability, low intensity noise, and perfect beam quality[1]. Among those lasers with diverse output wavelengths, the all-solid-state single-frequency lasers with the operating wavelength of 1.08 μm as promising light sources have been demonstrated to directly generate the continuous variable non-classical light fields by only utilizing one *a*-cut type-II non-critical phase-matching $KTiOPO_4$ (KTP) crystal[2–6]. The achieved non-classical light fields act as the basic resources of the quantum computing (QC) and quantum information network (QIN). Therefore, the single-frequency CW 1.08 μm lasers can be broadly applied in quantum optics and quantum technologies. Moreover, because the wavelength of 1.08 μm corresponds to the cesium 6S → 7S two-photon transition[7], the single-frequency 1.08 μm lasers can also be applied in atomic physics. In order to precisely match the cesium 6S → 7S two-photon transition line, it is required to realize the frequency tuning of the single-frequency CW 1.08 μm lasers. In recent years, the Nd:$CaYAlO_4$ (Nd:CYA) crystal as a candidate to emit the wavelength of the 1.08 μm laser has become more and more popular. In addition, several intrinsic advantages of the Nd:CYA crystal make it suitable for being used to generate the 1.08 μm lasers. Firstly, its absorption peak falls just around 807 nm ($^4I_{9/2} \rightarrow {}^4F_{5/2} + {}^2F_{9/2}$)[8], which corresponds to the wavelength of the most mature laser diode (LD). Then, benefiting greatly from the disordered crystal structure[9,10], the Nd:CYA crystal has large inhomogeneous absorption (full width at half-maximum is 5 nm) and emission broadened spectra (full width at half-maximum is 20 nm). The spectral properties of the Nd:CYA crystal makes it a good candidate to attain tunable and ultrafast lasers[8]. Owing to these desirable characteristics, a large number of CW transverse electromagnetic (TEM_{00}) mode lasers and tunable *Q*-switched lasers based on the Nd:CYA crystal have been studied. In 1989, Haracio *et al.* firstly, to the best of our knowledge, presented the laser action of Nd:CYA crystal and proved that CYA was a good host for rare-earth ions, and the maximum output power of the CW TEM_{00} mode at 1.08 μm was about 80 mW[9]. Stephens *et al.* further showed the continuous tunable single-mode laser of the Nd:CYA crystal from 1077.5 to 1084.5 nm with a Lyot filter in the resonator and the maximum output power with only 15 mW in 1992[10], which further confirmed that the emission spectra were broadened enough to be used for tuning and optically pumping metastable helium atoms. Yu *et al.* demonstrated a 5.16 W CW 1.08 μm laser with a Nd:CYA crystal and further obtained a passively *Q*-switched laser with a Cr:YAG in the cavity in 2010[11]. In 2011, Fu *et al.* reported a CW frequency-doubled green laser at 540 nm in KTP crystal in a type-II phase-matching direction performed with a diode pumped Nd:CYA laser. The output power of 540 nm laser reached 324 mW, and its beam quality was 1.34 and 1.22 when the pump power was 18.2 W[12]. Because of the multi-mode operation, there was cross saturation in the Nd:CYA crystal, sum frequency in the KTP crystal, and large fluctuation of the output power. However, up to now, there is no report on a stable CW single-longitudinal-mode (SLM) tunable laser based on Nd:CYA crystal, to the best of our knowledge. In this paper, we first, to the best of our knowledge, report a CW single-frequency tunable CW Nd:CYA laser with good performance. The output power of the single-frequency 1.08 μm laser reaches up to 1 W. The maximal and continuous tuning ranges of the 1.08 μm laser are up to 183.71 GHz and 60.72 GHz, respectively. The results prove that it can be an excellent source for QIN and QC.

2. Experimental Design

The configuration of the designed CW single-frequency tunable 1.08 μm laser system is shown in Fig. 1. The figure-eight-shaped ring cavity with the length of 283.84 mm is formed by two plane mirrors M_1, M_2 and two plane-concave mirrors M_3, M_4. The curvature radii of both concave mirrors are 50 mm. The input coupler M_1 is coated with high transmission (HT) film at 808 nm ($T_{808} > 95\%$) and high reflection (HR) film at 1.08 μm ($R_{1080} > 99.5\%$). M_2 is coated with partial transmission film ($T_{1080} = 4\%$). M_3 is coated with HR film at 1.08 μm ($R_{1080} > 99.5\%$). M_4 is a dichroic mirror coated with HR film at 1.08 μm ($R_{1080} > 99.5\%$) and HT film at 540 nm ($T_{540} > 95\%$). The pump source is a fiber coupled LD with the output power of 15 W at 808 nm (Dilas). Through scanning the LD's temperature, its wavelength could be precisely tuned to the maximum absorption peak of the Nd:CYA crystal. The core diameter and numerical aperture (N. A.) of the fiber are 400 μm and 0.22, respectively. A telescope system, consisting of two lenses f_1 and f_2 with focal lengths of 30 mm and 50 mm, respectively, is designed to focus the pump light at the center of the gain medium. The gain medium is an *a*-cut Nd:CYA crystal with the dimensions and Nd-doping concentration of $3\,mm \times 3\,mm \times 6\,mm$ and 1% (atomic fraction), respectively. It is wrapped with indium foil in a copper oven to realize timely temperature adjustment. The temperature of the Nd:CYA crystal is set as 27.79°C. Both ends of the crystal are coated with anti-reflection (AR) films at both 808 nm and 1.08 μm. The optical diode (OD), composed by a terbium scandium aluminum garnet (TSAG) crystal with the size of $\phi 4\,mm \times 4.5\,mm$ surrounded by permanent magnet and a half-wave plate (HWP), is inserted into the resonator to ensure the unidirectional operation of the laser. Compared to a terbium gallium garnet (TGG) magneto-optic crystal, the TSAG crystal plays a greater role in better magneto-optical rotation. A type-I phase-matching lithium triborate (LBO) crystal[13] with the dimensions of $3\,mm \times 3\,mm \times 15\,mm$ is placed at the beam waist between the mirrors M_3 and M_4 to introduce sufficient nonlinear loss to efficiently suppress the multi-mode oscillation and mode-hopping phenomenon[14,15]. The operating temperature of LBO is set as 136.9°C, which corresponds to the optimum phase-matching value of 1.08 μm laser. In order to further realize the continuous frequency tuning of the laser, an intracavity etalon (IE) made of fused silica with the thickness of 0.5 mm is inserted into the cavity. A long piezoelectric transducer (PZT) is mounted on M_3 to realize continuous scans of the cavity length by applying voltage to it. Most output of the 1.08 μm laser from M_2 is reflected by M_5 to monitor and record the power of the 1.08 μm laser. The leaked laser from M_5 is split into two parts by M_6. One part is coupled into the photodetector (PD) to lock the IE with the assistance of the homemade servo controller (SC). The other part is injected into the wavelength meter (WLMWS6, HighFinesse) to monitor the wavelength of the output laser.

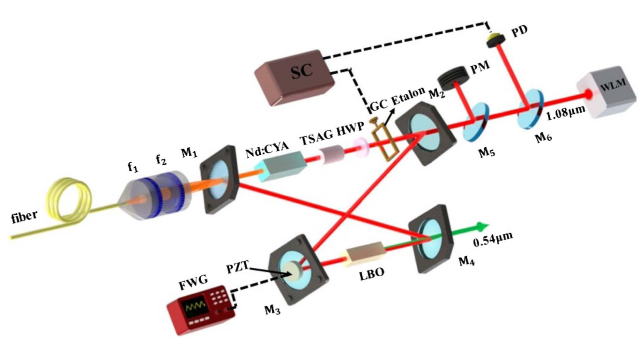

Fig. 1. Schematic diagram of the LD-pumped CW SLM tunable dual-wavelength 1.08 μm and 0.54 μm laser. HWP, half-wave-plate; GC, galvanometer scanner; SC, servo controller; PM, power meter; PD, photodetector; WLM, wavelength meter; FWG, function waveform generator; PZT, piezoelectric transducer.

It is well known that the equivalent thermal lens is a critical parameter for the cavity design of diode-pumped all-solid-state lasers[16]. The thermal conductivities of the Nd:CYA crystal are $3.7\,W/(m \cdot K)$ (parallel to *a* axis) and $3.3\,W/(m \cdot K)$ (parallel to *c* axis)[17–19], and the thermo-optical coefficients are $-7.8 \times 10^{-6}\,K^{-1}$ (parallel to *a* axis) and $-8.7 \times 10^{-6}\,K^{-1}$ (parallel to *c* axis)[20]. According to Ref. [20], the thermal coefficient of the optical path $[W = dn/dT + (n-1)\alpha]$ is measured as $1.2 \times 10^{-6}\,K^{-1}$ for $E \perp c$ polarization of *a*-cut Nd:CYA crystal, where n is the refractive index ($n_o = 1.886$, $n_e = 1.909$), and α is the thermal expansion coefficient ($\alpha_a = 10.2\,K^{-1}$, $\alpha_c = 10.2\,K^{-1}$). Benefiting from the negative thermo-optic coefficients as well as the small and positive thermal coefficients of the optical path, the equivalent thermal lens of the Nd:CYA crystal is relatively weak. The calculated stability range depicted in Fig. 2 is broad enough to obtain a stable single-frequency CW 1.08 μm laser. In order to obtain greater gain under the low pump power with the CW pumping mode, the waist radii of the pump laser and oscillating laser at the middle of the Nd:CYA crystal are designed as 320 μm and 365 μm, respectively, after taking the equivalent thermal lens focal length of the Nd:CYA crystal into account.

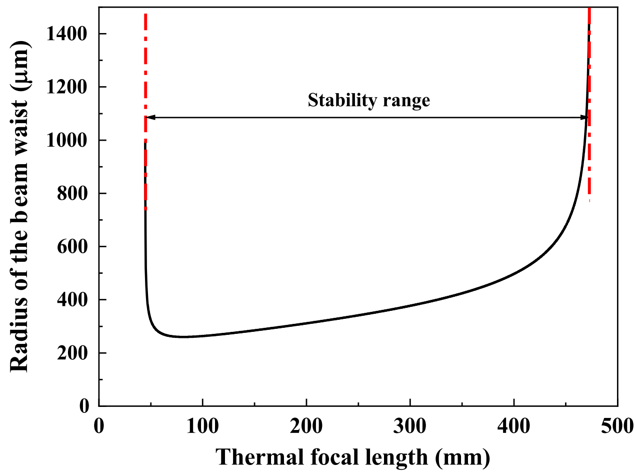

Fig. 2. Radius of the beam waist in the position of the Nd:CYA crystal versus the thermal focal length.

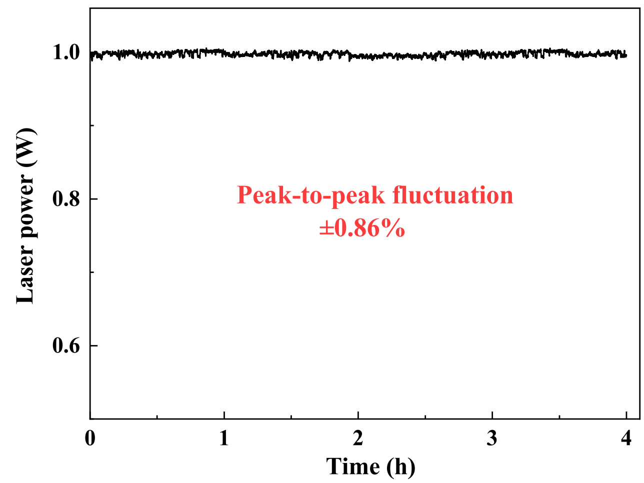

Fig. 4. Measured power stability of the 1.08 μm laser in 4 h.

3. Experimental Results and Discussion

After precisely optimizing the laser system, the stable tunable dual-wavelength laser with good performance is obtained. The output powers of the 1.08 μm and 0.54 μm lasers are recorded by a power meter (PM30, Coherent Co., Ltd.), as illustrated in Fig. 3. The results show that the threshold power of the 1.08 μm laser is 10.53 W. The maximum output powers of the 1.08 μm and 0.54 μm lasers reach 1 W and 34.9 mW, respectively, with the pump power of 13.08 W. The slope efficiency of the 1.08 μm laser is up to 38.04%. The polarization degree of the output 1.08 μm laser is measured by a polarization analyzer (PAX1000IR1/M, Thorlabs Co., Ltd.). The polarization ratio of the 1.08 μm laser is better than 100:1, which is ascribed to the high gain of $E \perp c$ polarization for the Nd:CYA crystal. The power stability of the 1.08 μm laser in 4 h is recorded in Fig. 4, which illustrates that the power stability is better than ±0.86%. The transverse-mode beam quality of the 1.08 μm laser is measured by employing an M^2 meter (M2SET-BP209IR/M, Thorlabs Co., Ltd.). The measured spatial beam profiles as well as corresponding caustic curves are shown in Fig. 5. The results show that the beam qualities of the 1.08 μm laser are $M_x^2 = 1.11$ and $M_y^2 = 1.06$, respectively. The longitudinal-mode structure of the laser is monitored by a scanned temperature-controlled Fabry–Perot cavity (F-P-100, Yuguang Co., Ltd.). The free spectral range (FSR) and finesse of the F-P cavity are 750 MHz and 120, respectively. From the monitored transmission curve shown in Fig. 6, it can be seen that the stable SLM operation is achieved, which benefits from the sufficient nonlinear loss introduced by the frequency-doubled crystal LBO. To the best of our knowledge, it is the first time to achieve a CW single-frequency tunable Nd:CYA laser.

Combining the IE and Nd:CYA crystal with a broad-band fluorescence spectrum, the wide tuning characteristics of the CW SLM Nd:CYA laser are investigated. Through rotating the incident angle of the inserted IE by continuously varying the voltage supplied to the galvanometer scanner (GC), the

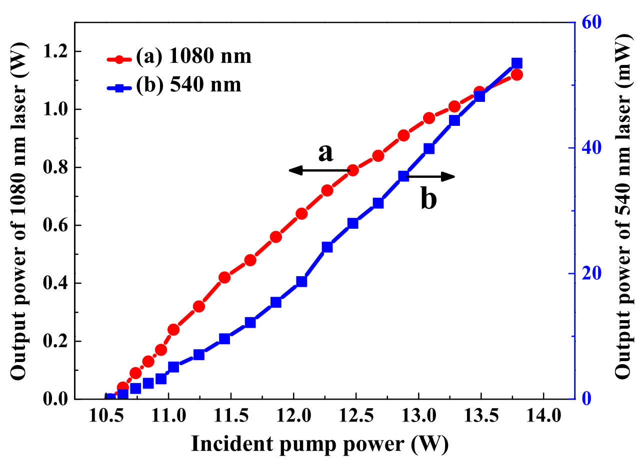

Fig. 3. Output power of 1.08 μm and 0.54 μm lasers as a function of the incident pump power.

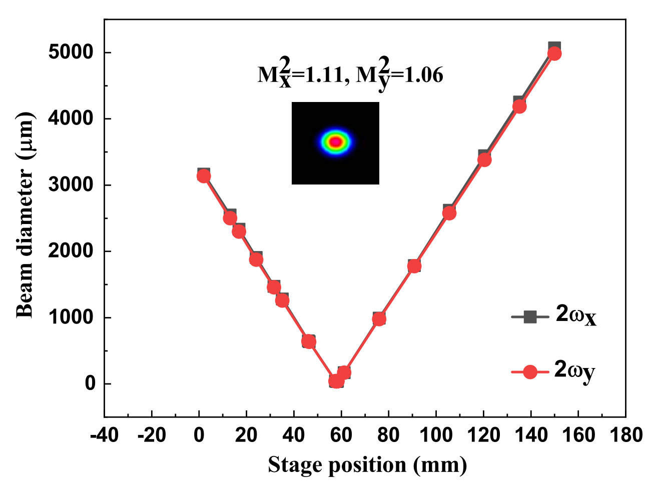

Fig. 5. Beam quality of the 1.08 μm laser.

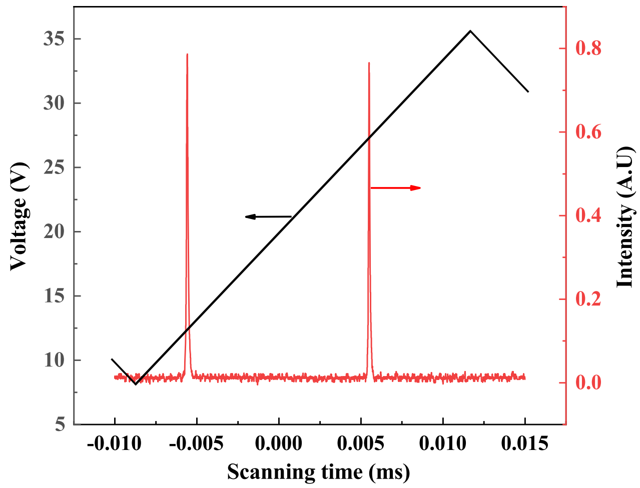

Fig. 6. Monitored longitudinal-mode structure of the 1.08 μm laser.

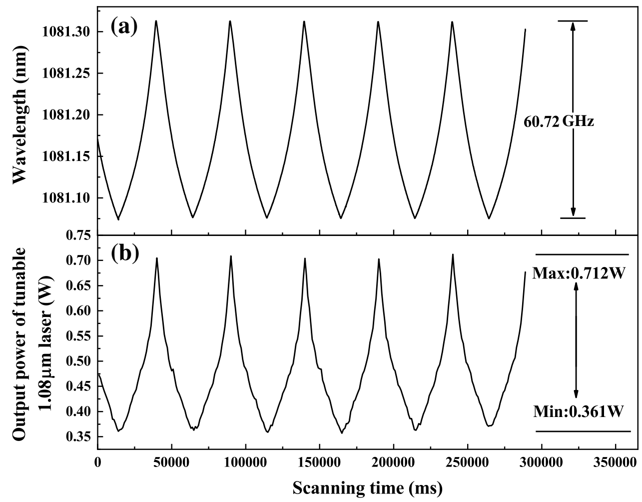

Fig. 8. Experimental results of the continuous frequency tuning. (a) Continuous frequency tuning of the 1.08 μm laser versus scanning time. (b) Corresponding power variation of the 1.08 μm laser in the process of continuous frequency tuning.

coarse tuning ability of IE is firstly recorded by the wavelength meter in Fig. 7. When the incident angle of IE is 0°, the laser wavelength is 1081.4007 nm. With the increase of the voltage supplied to the GC from 0 V to 1.98 V, the wavelength discontinuously decreases from 1081.4007 nm to 1081.1207 nm. In the case of 1.98 V supplied to the GC, the obvious wavelength-hop between 1081.1207 nm and 1081.8282 nm is observed. When further increasing the voltage from 1.98 V to 3.663 V, the measured output wavelength shifts to a shorter wave from 1081.8282 nm to 1081.1120 nm. The experimental results illustrate that the tuning range of the IE is 183.71 GHz, which is consistent with the FSR of the adopted IE. Further, in order to implement the continuous frequency tuning of the laser, we build a phase-lock system consisting of a photodiode (ETX 500, JDSU Corporation), function generator (FG), and homemade SC to lock the IE to the oscillating longitudinal mode of the laser[21,22]. After the transmission peak of the IE is locked to the oscillating longitudinal mode of the laser, continuous tuning with free mode-hopping is successfully realized. At this time, the

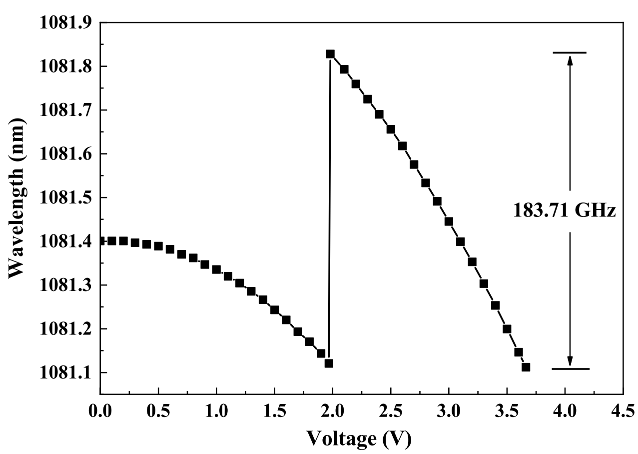

Fig. 7. The Maximum tuning range of the 1.08 μm laser by rotating the incident angle of IE.

length of the resonator is continuously scanned by loading a voltage scanning signal with the amplitude and frequency of 150 V and 20 mHz, respectively, onto the PZT. As depicted in Fig. 8(a), the fine and continuous wavelength tuning range of 60.72 GHz at 1.08 μm is achieved. It can also be concluded from Fig. 8(a) that the output wavelength of the 1.08 μm laser varies as nonlinearly as the scanning time increased, which results from the nonlinearity of the PZT. The highest tuning speed of output wavelengths is 3.679×10^{-5} nm/ms. It is expected that the broader continuous frequency tuning range of the CW SLM Nd:CYA laser could be attained if a PZT with longer displacement is employed in the experiment. In the tuning process, a fraction of the output power of the achieved tunable single-frequency CW 1.08 μm laser at different tuning wavelengths is simultaneously monitored, and the results are shown in Fig. 8(b). The results depict that the periodic variation trends of the output power are similar to that of the continuous frequency tuning. The maximum and minimum output powers of the tunable 1.08 μm laser are 0.712 W and 0.361 W, respectively.

4. Summary

In summary, we first realize a CW single-frequency tunable 1.08 μm laser by utilizing a Nd:CYA crystal as the laser medium, to the best of our knowledge. The maximal output power of the 1 W CW SLM 1.08 μm laser is attained with the slope efficiency of 38.04%. The measured peak-to-peak power stability in 4 h and beam qualities of the 1.08 μm laser are ±0.86% and $M_x^2 = 1.11$, $M_y^2 = 1.06$, respectively. Through inserting an IE with thickness of 0.5 mm into the cavity, the maximal tuning range of 183.71 GHz and continuous tuning range of 60.72 GHz with the free mode-hop of the single-frequency 1.08 μm are achieved. The presented CW SLM tunable 1.08 μm laser with good performance could be applied in atomic physics to precisely match the cesium 6S → 7S two-photon transition line.

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