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Continuous-wave yellow laser generation at 578 nm by intracavity sum-frequency mixing of thin disk Yb:YAG laser and Nd:YAG laser

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ABSTRACT

We report a continuous-wave yellow laser at 578 nm obtained by doubly resonant intracavity sum-frequency mixing of thin disk Yb:YAG laser and Nd:YAG laser with a LBO nonlinear crystal. Single-wavelength laser operation at 578 nm by using a silica etalon as a wavelength selector and dual-wavelength operation at 578 nm and 582 nm are obtained with maximum output powers of 100 mW and 136 mW, respectively. The single wavelength operating power stability value in 30 min was ~4.7%, which was improved ~21.6%, compared with that of dual-wavelength operation.

1. Introduction

Diode-pumped solid-state lasers operating in the yellow region have received a great deal of attention in the past decades for a number of applications [1–4]. In medical applications, yellow lasers are desirably used for dermatological treatment due to increased interaction between the photon and hemoglobin, where the wavelength of the light matches the differential absorption peak between photon and hemoglobin [5]. In fluorescence microscopy imaging areas, different wavelengths of yellow-orange sources are applied to excite the corresponding chromophores for signal detection, without exciting background fluorescence [6]. Narrow-line operation of these laser sources with high frequency stability is of further interest in spectroscopy and remote-sensing applications [7].

However, no efficient semiconductor materials direct emit in this spectral region. Though it is recently demonstrated that the shortest wavelength in the yellow-orange region is 599 nm via direct emission by GaInP material, the efficiency of the system used in this case is rather modest [8]. The development of frequency doubling of optically pumped vertical-external-cavity surface-emitting semiconductor laser has become one of the solutions [9]. When considering the laser's size, cost, efficiency and stability, another attractive path to generate yellow laser is all-solid-state laser systems with the use of nonlinear frequency conversion technology. In the case of pulsed operation with high peak power, intracavity frequency-doubled Raman-shifted Nd^{3+} laser to the region is a promising approach [10,11]. Besides, sum frequency generation (SFG) of two transitions lines is an alternative important approach to generate yellow-orange laser. One way to obtain dual wavelength laser transition is to use different energy levels of the excitation in one single crystal. Several papers have been published the realization of the yellow-orange radiation at 593.5 nm through SFG of two emission lines from transitions $4F_{3/2}$–$4I_{11/2}$ (~1.06 μm) and $4F_{3/2}$–$4F_{13/2}$ (~1.3 μm) of Nd doped lasers [12–14]. Using doubly resonator for intracavity sum frequency mixing in two different cavities sharing a overlapped cavity has long become another important approach of generating coherent radiation in the yellow-orange spectral region [15]. Benefiting from this scheme, the laser spectrum could be expanded due to the two independent gain mediums with separate pump source, and the competition between the two fundamental frequency lasers is avoided. Using this doubly resonator structure, we had reported a compact ~578 nm yellow laser in which a thin disk Yb:YAG single crystal and a Nd:YAG single crystal were employed to generate two fundamental waves (1319 and 1030 nm). With a total incident pump power of 14 W, a maximum output power of 37.5 mW yellow laser was obtained by the use of a type-I critically phase matched LBO crystal for SFG [16].

In this paper, we show a compact cw yellow laser source at 578 nm using by doubly resonant with a folded overlapped cavity. The

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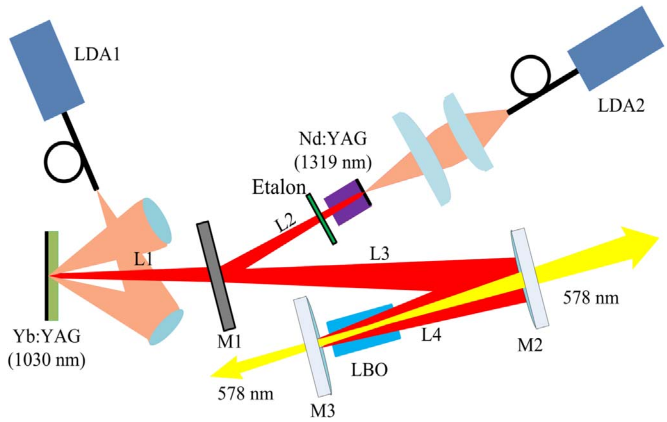

Fig. 1. Schematic of the intracavity SFG of 578 nm yellow laser. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

intracavity sum-frequency mixing of thin disk Yb:YAG laser and Nd:YAG laser is realized by a LBO nonlinear crystal in the folded common arm. Two wavelength operation at 578 nm and 582 nm are obtained with maximum output power of 136 mW and single-wavelength laser operation at 578 nm is obtained with maximum output power of 100 mW by using a glass etalon as a wavelength selector.

2. Experimental setup

The schematic of the laser setup is illustrated in Fig. 1. Two gain mediums, the Yb:YAG single crystal (with a disk laser setup) and the Nd:YAG single crystal were used to generate the two fundamental 1319 nm and 1030 nm waves, respectively. The thin-disk 10 at %-doped Yb:YAG crystal, having a 11 mm diameter and 0.42 mm length, was mounted with one face on a water-cooled copper heat sink. The temperature of Yb:YAG crystal cooled by flowing water was maintained at 20 °C with an accuracy of 0.1 °C. The pumping side of the Yb:YAG crystal was antireflection (AR) coated at 940 nm (T > 99.6%) and 1030 nm (T > 99.9%). The cooling side of the Yb:YAG crystal was high reflection (HR) coated at 940 nm and 1030 nm (R > 99.9%). LDA1 (diameter of 300 µm and numeral aperture of 0.22) emitting at the wavelength of ~940 nm was used to pump Yb:YAG disk crystal for 1030 nm oscillation. Considering the quasi-three-level characteristics of Yb:YAG crystal, four-pass pump configuration was completed by using a pair of mirrors which had high reflection at 940 nm. The other gain medium, a Nd:YAG rod (Φ5 mm×6 mm) doped with 1 at% concentration of Nd^{3+} was chosen for the experiments. The crystal was wrapped into an indium foil and mounted on a copper heat sink. The pumping side of the Nd:YAG was AR coated at 808 nm (T > 95%) and HR coated at 1319 nm (R > 99.9%). The opposite side was AR coated at 1319 nm (T > 99.8%). LDA2 (diameter of 200 µm and numeral aperture of 0.22) emitting at the wavelength of ~808 nm was employed as the end-pumping source for generating 1319 nm oscillation. With a collimating plano-convex lens of 40 mm focal length and a focusing plano-convex lens of 60 mm focal length, the end face of the fiber was imaged into the laser crystal with a spot radius of 150 µm. Both of the central emission wavelengths of the pump sources could be changed by tuning the operating temperature to match the absorption peaks of the two kinds of laser gain medium.

The experimental setup comprises a V-shaped cavity for the 1030 nm oscillation and a Z-shaped cavity for the 1319 nm oscillation with a common arm. The pumping side of Nd:YAG crystal and the cooling side of Yb:YAG crystal acted as their own cavity mirrors respectively. Mirror M1 which was HT coated at 1030 nm and 1064 nm (T > 99.8%) on both sides and HR coated at 1319 nm (R > 99.9%) on the right side played a role as a beam splitter for the two fundamental wavelengths, separating the cavity for the two laser

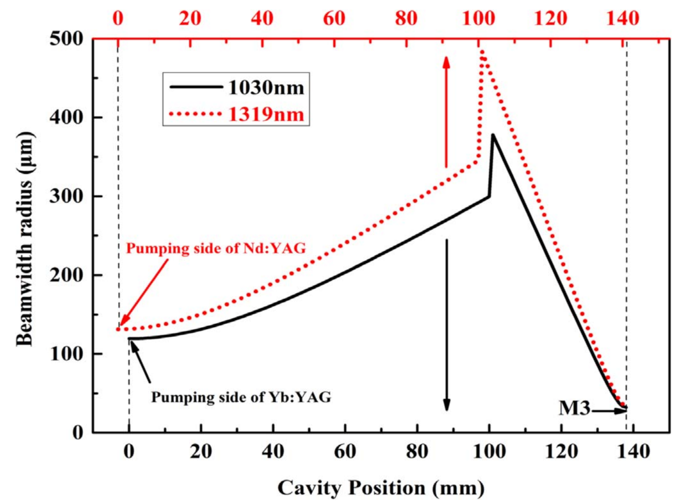

Fig. 2. Intracavity beam width radius of fundamental waves.

crystal. M1 was designed HT at 1064 nm to suppress the more efficient transition line at 1064 nm in the Nd:YAG crystal. The folded output mirror (M2) which had a radius of curvature of 50 mm was AR coated at 578 nm (T > 96%) and HR coated at 1030 nm and 1319 nm (R > 99.9%). The end output mirror (M3) was coated the same as M2 and had a radius of curvature of 200 mm. A Type-I CPM LBO crystal (3×3×7 mm3, θ=90°, φ=5°) was used to produce SFG at 578 nm. The LBO crystal was placed in a copper holder and temperature maintained together with Nd:YAG crystal by a thermal electric cooler (TEC) with a precision of ± 0.1 °C. The V-shaped and Z-shaped cavities were designed to be stable by using the standard ABCD matrix method. The designed arm lengths of the two separate arms L1 and L2 were found to be optimal at ~55 and ~58 mm, respectively. The corresponding length of the common arm L3 and L4 were ~52 and ~31 mm, respectively. Both of the fundamental beam waists located close to M3 (see Fig. 2). The value of the ratio ω2/ω1 was ~1.06, where ω1 (~33 µm) and ω2 (~35 µm) were the beam waist size in the LBO crystal for wavelengths 1030 nm and 1319 nm, respectively. The designed arm lengths were readjusted slightly upon the SFG laser operation.

3. Results and discussion

As the 1338 nm transition line is very close to the 1319 nm and it has a stimulated emission cross section about 2.2% weaker than that of 1319 nm transition line [17], both of the laser lines are easily to oscillate synchronous in the Nd:YAG laser cavity. A fiber spectrometer (NIRQuest512, Ocean Optics, Inc.) with a resolution of ~2.0 nm (5 µm slit, 150 lines/mm blazed grating) was employed to monitor the infrared laser spectrum. The measured spectrum of 1319 and 1338 nm laser is shown in Fig. 3(a). It was obvious that the 1338 nm laser line hold a rather high percentage as a precondition for the simultaneous laser operation of the two yellow laser wavelengths. Though the cutting angle of LBO was designed for 1030 and 1319 nm fundamental waves to SFG at 578 nm, the maximum acceptance angle of LBO is 20 mrad for SFG of 1030 nm and 1319 nm, which is two times larger than the angle difference (Δφ=0.5°) between SFG of 578 nm and 582 nm. A fiber spectrometer (Maya2000Pro, Ocean Optics, Inc.) with a resolution of ~1.1 nm (25 µm slit, HC-1 grating) was employed to monitor the yellow laser spectrum. As a result, we observed the simultaneous dual-wavelength lasing at 578 and 582 nm (see Fig. 4(a)). The relative intensities of 578 and 582 nm would be changed by tuning the angle of the LBO crystal which is directly correlated with the SFG conversion efficiencies.

To enforce laser operation at 578 nm, an appropriate selective element, namely a simple silica plate serving as etalon, was inserted

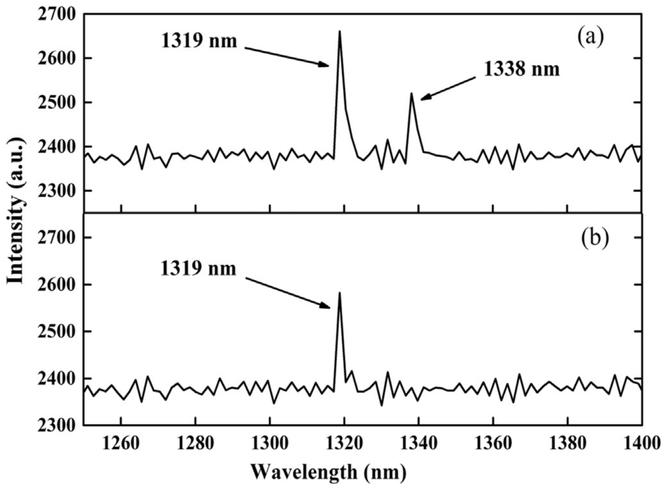

Fig. 3. The spectrum of infrared Nd:YAG laser. (a) Simultaneous dual-wavelength oscillating at 1319 and 1338 nm, (b) 1319 nm laser line selected with the silica etalon.

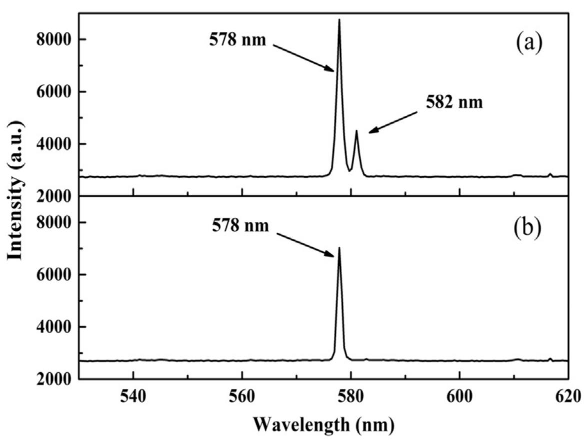

Fig. 4. The spectrum of the output yellow laser. (a) Simultaneous dual-wavelength operation at 578 and 582 nm, (b) single-wavelength operation at 578 nm selected with the silica etalon.

inside the laser cavity. The transmission of the etalon can be expressed as

$$T = \left[1 + \frac{4r}{(1-r)^2}\cdot\sin^2\left(\frac{\delta}{2}\right)\right]^{-1},$$

where δ is the round-trip phase difference of the laser and r is the reflectivity of the etalon surface. Based on the invariant parameters as a thickness d=0.18 mm, refractive index n=1.46 and surface reflectivity r =0.04 of the etalon, transmission of the silica etalon at different wavelengths could be calculated versus the tilt angle of the etalon. As can be seen from Fig. 5, the transmission curves of the two fundamental waves are clearly separated. It is convenience for us to adjust the inserting losses at the two lines, which is important for the control of the corresponding net gain inside the cavity and the consequential efficient single 1319 nm line oscillation. It is observed that the tilt angle =0.048 rad corresponds to a maximum transmission (100%) at 1319 nm and sufficient insertion loss (12%) to suppress the 1338 nm laser oscillation.

Fig. 6 depicts the characteristics of the cw yellow laser outputs versus the absorbed pump power of Nd:YAG crystal and the pump power of Yb:YAG crystal. Without inserting the etalon, the maximum dual-wavelength yellow laser output power of 136 mW was obtained, of which 82 mW was from M2 and 54 mW from M3, respectively. On this point, total pump power is 18.6 W, the pump power for Nd:YAG and Yb:YAG was 5.4 W and 13.2 W, respectively. We attribute the low

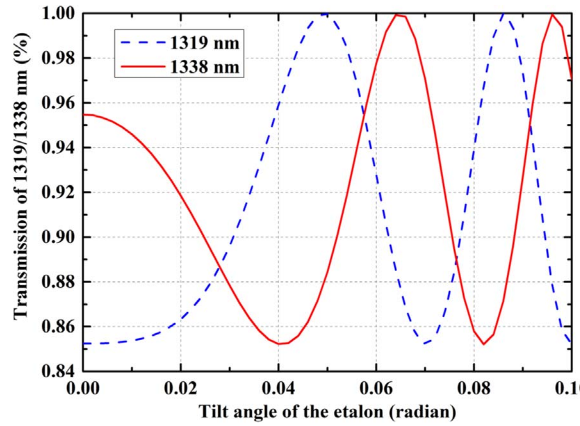

Fig. 5. Transmission curves for 1319 and 1338 nm lines varied with the tilt angle of the etalon.

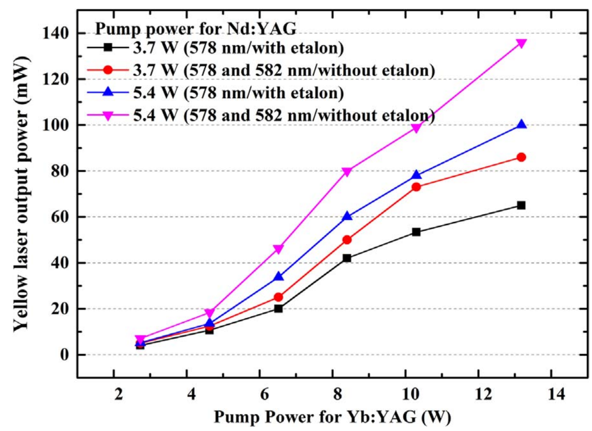

Fig. 6. Yellow laser outputs versus the pump power for Nd:YAG crystal and the pump power for Yb:YAG crystal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

utilization of 940 nm pump laser to two key points. One is the nature of Yb:YAG crystal, including the relative poor stimulated-emission cross section and the reabsorption of lower laser level according to the quasi-three-level characteristics of the Yb:YAG crystal [18,19]. The other is the inserting loss introduced by the beam splitter which is estimated as 0.2% according to the reflectance at 1030 nm of the beam splitter. With the total pump power of 14 W, 3.7 W for Nd:YAG and 10.3 W for Yb:YAG, the dual-wavelength yellow laser output power of 73 mW was obtained, which was almost twice that obtained from single-ended output in [16] with the same pump power. The improved SFG efficiency was due to the compressed fundamental waves' beam width formed in the folded common arm and twice SFG process of the two fundamental waves' round trip in the folded cavity. However, the improvement is not as significant as we expected. It is obvious that the lower SFG efficiency is due to the lower utilization of 940 nm pump laser and 1030 nm fundamental frequency laser. The further improvement of the SFG efficiency may be achieved by two ways. One way is to replace the copper heat sink with microchannel water-cooled copper heat sink to keep the temperature of Yb:YAG lower and the reabsorption of lower laser level could be decreased according to the quasi three-level characteristics of the Yb:YAG crystal. Thus the 1030 nm conversion efficiency of Yb:YAG would be improved. The other way is to reduce the reflective loss of 1030 nm introduced by the beam splitter M1 with high quality coating film. The SFG efficiency would be improved as the 1030 nm power increase within the resonator.

To obtain the single wavelength laser at 578 nm and avoid disturbing the oscillation of 1030 nm, the etalon was inserted in the cavity arm L2 in which only contained the Nd:YAG laser. As shown in

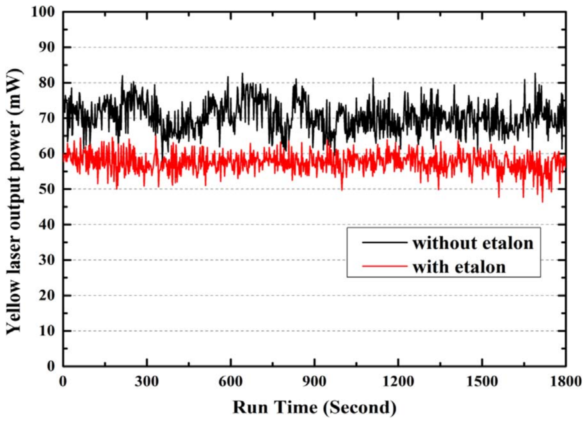

Fig. 7. Fluctuations of the yellow laser power at the maximum output level for conditions with and without the etalon inside the laser cavity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3(b), by adjusting the tilt angle of the glass etalon, single-wavelength operation at 1319 nm was obtained so as to realize the SFG single wavelength at 578 nm successfully when the LBO crystal was placed inside the folded common arm L4 (see Fig. 4(b)). The maximum single-wavelength 578 nm yellow laser output power was 100 mW with a total pump power of 18.6 W. The insertion loss of 1319 nm laser due to the silica etalon can be calculated as ~0.3% by using the expression used in [20]. However, due to the sufficient loss of 1338 nm by inserting the etalon, only the single-wavelength 1319 nm laser took part in SFG that results in a significant decrease of output power by a factor of 25%.

The transverse spatial profile and the beam propagation factors of the yellow laser beam were also measured with the knife-edge method using a M2–200 s-FW (Ophir-Spiricon, Inc.) laser beam analyzer. The M2 factors were approximately 1.6 and 1.4 in the horizontal and vertical directions, respectively. We considered that the astigmatism was mainly ascribed to the walk-off between the fundamental wave and the frequency mixed wave in the direction of LBO [13] and the folded angle in the cavity.

Finally, using the StarLab2.40 software from Ophir, Inc., we measured the power stability of single wavelength operation and dual-wavelength operation. As shown in Fig. 7, comparisons on the maximum output power fluctuations of the yellow laser, with and without the etalon inside the cavity, were performed in the given 30 min. The power stability value was enhanced ~21.6%, i.e., from ~6.0% to ~4.7%, when the silica etalon was inserted into the cavity. We attribute this result to the point that competition between the 1319 nm line and the 1338 nm lines was improved by the tunable net gains of the two lines.

4. Conclusion

A compact cw yellow laser source at 578 nm by the use of doubly resonant with a folded overlapped cavity and intracavity sum-frequency mixing of thin disk Yb:YAG laser and Nd:YAG laser with LBO crystal has been demonstrated. The dual-wavelength maximum output power of 136 mW and single wavelength of 100 mW was obtained at 18.6 W of total pump power. We believe that further increase of the cw yellow output power would be a realistic goal by improving the utilization efficiency of 1030 nm laser.

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