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Yellow light generation by frequency doubling of a diode-pumped Nd:YAG laser

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Abstract

We demonstrate the generation of TEM_{00} mode yellow light in critically type II phase-matched $KTiOPO_4$ (KTP) with intracavity frequency doubling of a diode-pumped Nd:YAG laser at room temperature. After a 150 μm thick etalon have been inserted into the cavity, the stability and beam quality of the second harmonic generation (SHG) is enhanced. A continuous wave (CW) TEM_{00} mode output power of 1.67 W at 556 nm is obtained at a pump level of 16 W. The total optical to optical conversion efficiency is about 10.44%. To the best of our knowledge, this is the first Watt-level yellow light generation by frequency doubling of Nd:YAG laser.

Keywords: Nd:YAG; DPSSL; 556 nm; KTP; Intracavity frequency doubling

1. Introduction

Recently, diode-pumped Nd-doped lasers have been developed as all solid state source in blue, green and red spectral region through intracavity frequency doubling. However, the region from 550 to 650 nm has been covered by these sources scarcely. Some yellow lights among this range locate at the peak absorption of several popular fluorescent dyes and high absorption in hemoglobin. Especially, laser sources with emission wavelength in the range from 550 to 560 nm are highly interesting. As their huge potentials in entertainments and medical applications, these sources have better penetration through nuclear sclerotic cataracts, excellent penetration through fluid and pigmentary disturbances, less dispersion of energy in the neurosensory retina, less discomfort to the patient, greater margin of safety than other sources in this spectral region. Traditionally, these sources are obtained by methods such as sum frequency mixing (SFM) of Nd:YAG or $Nd:YVO_4$ lasers [1–3], which is based on dual-wavelengths oscillating [4], frequency doubling of an intracavity Raman shifted Nd:YAG lasers [5,6], direct frequency doubling of the Cr:forsterite lasers [7], and copper vapor lasers and various dye lasers. However, these lasers were generally large in size, inefficient, complicated to operate, or highly toxic. In this paper, we obtained this efficient, stable, compact, and all solid state yellow source through intracavity frequency doubling of laser line at 1112 nm in Nd:YAG using laser diode arrays (LDA) as the pump source.

To our knowledge, the most popular laser line in Nd:YAG is 1064 nm which is superior to 1319 and 946 nm. In fact, there are about 30 laser lines in Nd:YAG [8]. The 1.1 μm waveband laser transitions from $^4F_{3/2}$ to $^4I_{11/2}$ (1112 nm: $R_2 \rightarrow Y_6$, 1123 nm: $R_1 \rightarrow Y_6$, 1116 nm: $R_1 \rightarrow Y_5$) have good laser performance. Among them, the 1123 nm laser line has been utilized extensively due to it's special applications in areas such as differential absorption lidar, Tm^{3+} doped up-conversion fiber laser, and so on [9–11]. The research report on the second harmonic generation (SHG) of 1112 nm Watt level has not presented to our knowledge. It is significant that the wavelength of the

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SHG of 1112 nm is 556 nm and close to 555 nm, at which, the optical reaction functions of the human eyes is maximum of, additionally, the lasers at 556 nm can be used as alternative to the currently used He–Ne 543 nm lasers and replacement of Kr 568 nm lasers.

2. Experiment setup

The experiment setup is shown in Fig. 1. The pump source is a 20 W fiber-coupled LDA manufactured by LIMO Corporation with emission wavelength at 808 nm, a core diameter of 400 μm and a numerical aperture of 0.22. CO is a couple optics systems, which is composed by two plane-convex lenses ($f = 10$ mm) and AR coated at 808 nm. The fiber output is imagined into the crystal at amplified ratio of 1:1. The laser crystal is a 1.0 at.% Nd^{3+} doped, ∅ 4 × 3 mm Nd:YAG crystal, it is wrapped with indium foil and mounted at a TEC (thermal electronic cooled) copper block, the temperature is maintained at 20 °C. The whole cavity is also cooled by TEC. The left facet of Nd:YAG is the input coupler with HR (high reflection) coatings at 1112 nm, AR (anti-reflection) coatings at 808 and HT (high transmittance) coatings at 1319 nm, the right facet of Nd:YAG is AR coated at 1112 nm. M_1 is a 50 mm radius-of-curvature plane-concave output coupler, the left facet with high reflection coatings ($R > 99.9\%$) at 1112 nm and high transmittance coatings ($T > 95\%$) at 556 and 1064 nm, the right facet of the mirror is AR coated at 556 nm. M_2 is a 200 mm radius-of-curvature concave mirror with high reflection at 1112 and 556 nm. The etalon is a 150 μm thickness fused quartz without coatings. KTP (3 × 3 × 8 mm) is a frequency doubler (type II phase-matched cut, $\theta = 77.9°$, $\phi = 0°$) AR coated at 1112 and 556 nm.

The cavity is a three mirrors folded configuration with two beam waists (ω_{01}, ω_{02}), ω_{01} near the laser crystal, the other beam waist ω_{02} near the left side of M_2. The length of the cavity arms L_1 and L_2 are about 67 and 37 mm, respectively. According to the experiment setup, the thermal focal lengths are approximated to 83 mm. After numerical calculating, ω_{01} and ω_{02} are about 141 and 62 μm, ω_1 ($\omega_1 = 150$ μm) is the spot size of the laser mode at the laser crystal, ω_p ($\omega_p = 200$ μm) is the spot size of pump source. The ratio of ω_1 to ω_p is about 0.75 and satisfied the mode-matched criteria of end-pumped lasers at high pump level.

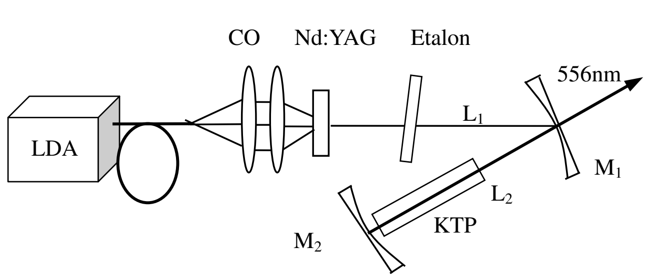

Fig. 1. The schematic of the experiment setup.

When tuning the temperature control of the pump source and aligning each component to good state, the color of the fluorescence in Nd:YAG is blue due to the excited state absorption (ESA) of the upper laser level. Unfortunately, the output coupler of the fundamental wave is not available, so the experiment data of the fundamental output vs. the pump power is not presented. We insert LBO and etalon into the cavity, and then tune their aligning angle till the output power of the SHG reached maximum. At the same time, we change the tilted angle of the etalon continuously and investigate the color of the output light is changed, these light at 556, 558 and 561 nm can obtain, respectively. In this paper, the light source at 556 nm is demonstrated for example.

3. Results and discussions

The free spectral range (FSR) of the 150 μm thick etalon ($FSR = \lambda^2/2nd$, $d \approx 150$ μm, $n \approx 1.41$) is about 2.9 nm, it is vital to the laser operation in our experiment setup stably. Without etalon, the output beam is multi-mode, which is mostly result from the mode competitions transversally and longitudinally among the 1.1 μm laser transitions (1112, 1116, 1123 nm). These competitions are intensively and lead to gain population in some pump region is just utilized by one or two laser lines among the 1.1 μm transitions. The difference in mode distribution of the three laser lines lead to the undesirable spatial superposition and beam quality of the SHG. With etalon inserted, not only the TEM_{00} mode is obtained, but also the output power fluctuation is reduced. This phenomena is clarified that the fundamental light operated stably at 1112 nm independently and without competition to the other laser lines of Nd:YAG (1116, 1123 nm). After the etalon is inserted into the cavity, tuned its tilted angle to an appropriated value, at which, 1112 nm laser line is just located at the peak of the transmittance curve, the 1116 and 1123 nm laser oscillation are suppressed by the inserting losses of the etalon.

Having numerical modeling, we investigate many proper tilt angles of the etalon, at which, only the 1112 nm laser line is oscillated, the other two laser lines are suppressed by higher inserting losses of the etalon. The schematic of the etalon as a line selector is shown in Fig. 2. In this figure, the cosine value of the light inserted on the etalon is 0.9901 and the degree of the corresponding tilted angle is about 8.0, the transmittance at 1112, 1116 and 1123 nm are about 1.000, 0.877 and 0.881, respectively, large inserting losses of the etalon at 1116 and 1123 nm restrained the two laser lines from oscillating. The gain width of the laser line in Nd:YAG is about 0.5–0.6 and the longitudinal modes difference of the cavity is about 0.011 nm, in addition, the Nd:YAG is a average-widen laser crystal, it is estimated that there are less than 10 longitudinal modes in the cavity. Although the etalon can use as a frequency selector, the 150 μm thick etalon is difficult in obtaining single frequency operation in current setup. This fact indicates that

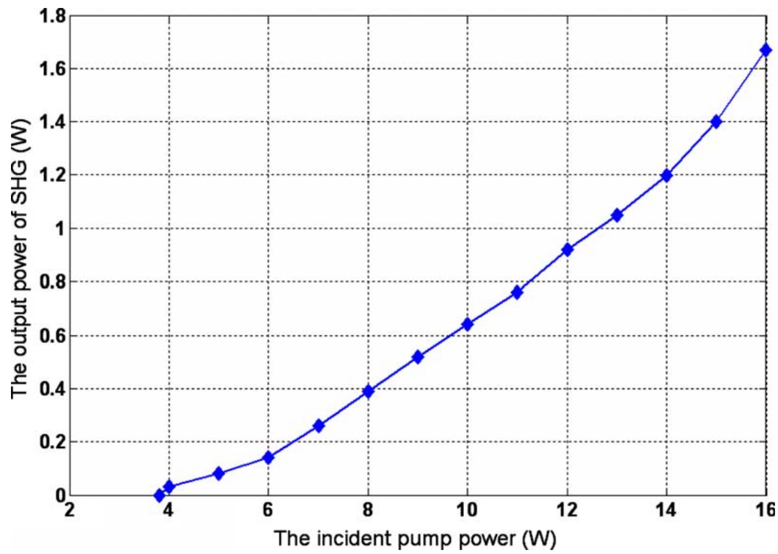

Fig. 2. The schematic figure of the etalon as a line selector.

the etalon is mainly acted as a line selector and not as a frequency selector. The feasibility of this method also has been identified particularly by numerical calculations, the relative report will to be published before long.

Using power meter (Field Master-GS) to measure the output power of SHG, the curve of it as a function of the incident pump power is shown in Fig. 3. It is shown that the threshold of the 556 nm lasers is about 3.8 W, and the maximum output power is 1.67 W at the incident pump power of 16 W, and the optical to optical conversion efficiencies is about 10.44%. The measurement statistics indicate that the fluctuation of the SHG output power were less than 5% in 4 h working. It is pleasantly surprised to us that the gray-track effect in KTP has not been investigated for a long-time operation. Using the LABRAM-UV spectrum analyzer to scan SHG and dealing with the data by software, the spectrum of the SHG laser is shown in Fig. 4. The large background noise was attributed to the low tolerable intensity of the detector in the spectral analyzer, the output light has been attenuated substantially before it is transmitted to the analyzer, so the background noise is amplified relatively.

In order to compare the SHG efficiencies of KTP with LBO, we used the same cavity configuration and

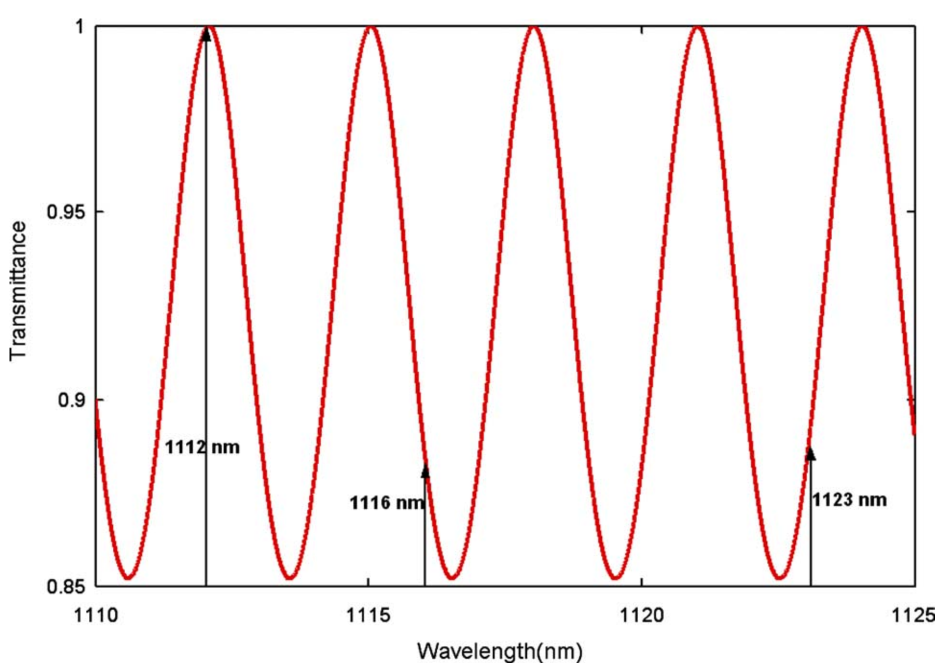

Fig. 3. The output power of SHG vs. the pump power.

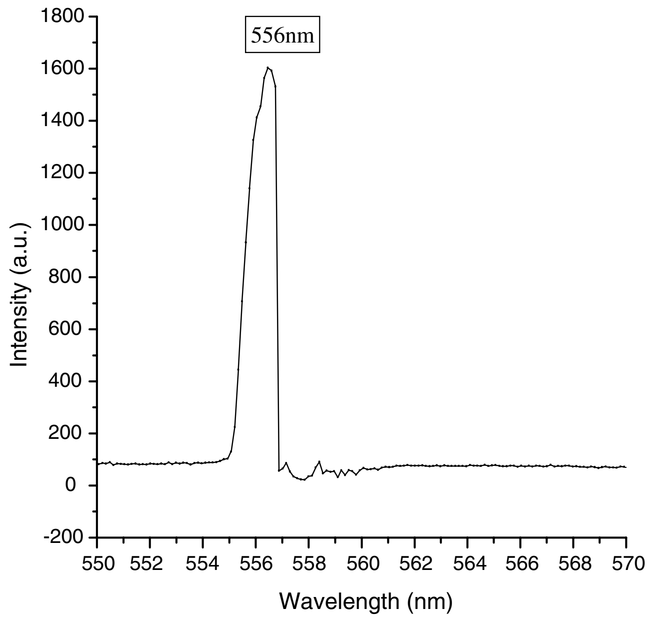

Fig. 4. The spectrum of SHG.

experiment conditions as shown in Fig. 1, except for using LBO ($2 \times 2 \times 10\ mm^3$, type I phase-matched cut, $\theta = 90°$, $\phi = 8.3°$) as a frequency doubler. Using LBO as the frequency doubler, the maximum of output power is about 1.41 W less than that of KTP, it is mainly attributed to larger coefficient of KTP ($d_{eff\,KTP} = 3.72$ (pm/υ), $d_{eff\,LBO} = 0.836$ (pm/υ)) than LBO, but the larger walk-off angle of KTP ($\rho_{KTP} = 23.79$ mrad, $\rho_{LBO} = 5.05$ mrad) determined the length of KTP crystal is shorter than that of LBO, consequently, it is reasonable that the total frequency conversion efficiency of KTP is not substantially higher than that of LBO.

4. Conclusion

In summary, we have used a three mirrors folded cavity to achieve Watt-level laser output at 556 nm, in order to improve the quality of it, a fused quartz etalon as a laser line selector has been inserted into the cavity, a desirable result has been obtained. A compact, efficient 1.67 W CW yellow laser has demonstrated for the first time to our knowledge. We believe that power scaling to more than 2 W of CW yellow laser output will be a realistic goal with further optimization.

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