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Diode-pumped Nd:YAG/LBO CW yellow laser at 588.9 nm*

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A design of diode-pumped Nd:YAG laser with a single crystal that generates simultaneous laser action at the wavelengths of 1 064 nm and 1 319 nm was presented and continuous-wave (CW) of 588.9 nm was obtained for the first time by use of type-I critical phase-matching LBO crystal intracavity sum-frequency mixing. The maximum output power of 62 mW is achieved with an incident pump power of 1.8 W. The optical-to-optical conversion efficiency is up to 3.4%, and the power instability in 24 h is better than ±2.7%.

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In recent years, diode-pumped all-solid-state lasers in blue[1], green[2] and red[3] spectral regins of intracavity frequency doubling were developed, because of their promising advantages, such as design simplicity, high efficiency, structure compactness. In medicine, optical testing, and color display technology[4], laser radiation from 550 nm to 650 nm is required. In particular, the yellow-laser at 588.9 nm radiation is very close to the Sodium D 2 at wavelength 589 nm, therefore it will become an ideal source instead of Sodium lamp. At present, the solid-state-laser techniques based yellow-laser output can be obtained by sum-frequency-mixing (SFM)[5-8], but most of them are *Q*-switched simultaneous dual-wavelength lasers, and extracavity-SFM are with lower efficiency and complexical structure.

A diode-end-pumped Nd:YAG laser with a single crystal collinear cavity is proposed for generation of stable simultaneous CW emission at the wavelengths 1 064 nm and 1 319 nm. By using type-I critical phase-matching LBO crystal intracavity SFM, the yellow laser at 588.9 nm was obtained for the first time. The maximum sum-frequency output power is up to 62 mW with 1.8 W pump power by optimizing the output mirror transmittance for 1 064 nm and 1 319 nm.

In a crystal, the electronic levels will further split into a number of Stark's sublevels. The transitions between the Stark's sublevels of different manifolds can emit laser with corresponding wavelength. Usually, the laser oscillates generally at one wavelength. Under special conditions, by introducing some linear or nolinear loss for the laser line which has a lower threshold to reduce its competition, the dual-wavelength lasing operation can be realized. Shen et al. [9] analyzed the possibility of simultaneous dual-wavelength lasers in Nd:YAG, Nd:YLF, Nd:YAP crystals at the transitions from $^4F_{3/2}-{}^4I_{11/2}$ and $^4F_{3/2}-{}^4I_{13/2}$, and realized that dual-wavelength operation of Nd-host crystal is more easier to accomplish with pulse operation than with CW operation. Their analysis showed that the ratio of stimulated-emission-cross (SEC) section between $^4F_{3/2}-{}^4I_{11/2}$ and $^4F_{3/2}-{}^4I_{13/2}$ transitions can not be too large for obtaining a CW dual-wavelength operation. Fig. 1 presents the Nd:YAG energy $^4F_{3/2}-{}^4I_{13/2}$ correspond to wavelengths 1 064 nm and 1 319 nm respectively. The 1 064 nm and 1 319 nm lines share the same upper level, and thus in dual-wavelength must compete. The SEC is 2.8×10^{-19} cm^2 for the $^4F_{3/2}-{}^4I_{11/2}$ transition and 0.56×10^{-19} cm^2 for the $^4F_{3/2}-{}^4I_{13/2}$ transition. Therefore the SEC ratio between the two transitions is 5 : 1. It is very difficult to obtain CW dual-wavelength operation. So the laser design and operation must combine to minimize these disadvantages. In order to optimize design parameters for high efficiency sum-frequency-mixing output, the standard expression for sum-frequency power in the small signal is utilized

$$P_3 = \text{const}\ P_1 P_2$$

where P_3 is the power at the sum-frequency obtained by mixing radiation of the two original frequencies of powers P_1 and P_2. To obtain high efficiency of sum-frequency-mixing, high power density for fundamental lasers is necessary, simultanelously photon numbers of the two fundamental wavelengths 1 064 nm and 1 319 nm in the cavity should be approximately equal, that is $N_{1064}=N_{1319}$, for $P_{1064}\propto h\upsilon_{1064}N_{1064}$, $P_{1319}\propto h\upsilon_{1319}N_{1319}$, υ_{1064} and υ_{1319} are the frequenices of the fundamental wavelengths 1 064 nm and 1 319 nm. So when N_{1064} is equal to N_{1319}, we can see $P_{1064}/P_{1319}=\upsilon_{1064}/\upsilon_{1319}=\lambda_{1319}/\lambda_{1064}=1319/1064=1.24$, the ratio of intracavity power for 1 064 nm and 1 319 nm should be approximately satisfied with 1.24. Because of the substantial gain difference between two wavelengths, to optimize high efficiency SFM, the loss value of each respective wavelength at the output

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coupler should be set to approximately balance the gain matching. In cavity design, the single collinear cavity was used, it could provide a rugged, compact solid¯state device which was designed simply, easily cailibrated, with a shorter cavity length and could exploit higher intracavity intensities and ensure a high degree of spatial overlap between the beams.

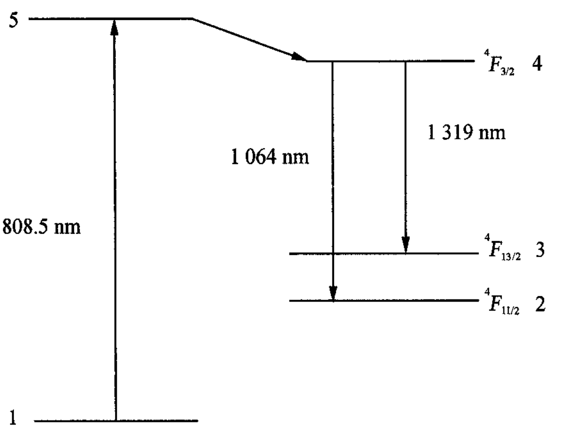

Fig. 1 The energy level of Nd:YAG crystal under study

Fig. 2 shows the experimental setup of SFM CW yellow laser. There are three parts in the setup: couple optics system, resonator system and temperature adjusting system. Pumping source is a laser diode with maximum output 1. 8 W, a central emitting wavelength 807. 5 nm at 23 ℃ and a divergent angle of 8. 2°×34. 5°. After going through the coupling optics, light emitted from the LD is rashaped to high-quality pumping light (with an ellipticity of 0. 91, beam waist's radius is about 95 μm), then is injected into Nd:YAG crystal (3 mm×3 mm×2 mm). The Nd^{3+} concentration of the crystal is 1. 0 atm%, the incident face of crystal is directly coated with dielectric reflective film as the resonator's end facet, the output mirror is a 50 mm radious-of-curvature concave mirror as the resonator's another facet. The resonator length is about 20 mm. The type-Ⅰ critical phase-matching LBO crystal 2 mm×2 mm×10 mm is used. When the two fundamental lasers simultaneously operated, by use of different nonlinear parameter LBO, sum-frequency generation of the two radiation wavelengths (1 064 nm and 1 319 nm) to produce yellow light (588. 9 nm) and second-harmonic generation of each fundamental radiation wavelength to produce red (660 nm) or green (532 nm) light could be achieved.

Data listed in Table 1 show the different LBO crystal nonlinear parameters. The temperatures of LD, Nd:YAG and LBO are strictly controlled by TEC1 and TEC2 respectively. The current of TEC1 is adjusted to make the central wavelength emitted from the LD to coincide with the absorption peak of Nd^{3+} in order to utilize the pumping light. Nd:YAG and LBO are cooled by the same cooler TEC2 to reduce thermal effect of Nd:YAG and kept the phase-matching condition of LBO from changing with environment. To generate simultaneous laser action at the wavelengths 1 064 nm and 1 319 nm, obtain the optimum power about sum-frequency-mixing, it is necessary to distribute the system optics component' strainsmittance and reflectence characteristic for 808 nm, 1 064 nm, 1 319 nm and 588. 9 nm. First of all, arranging the transmission power ratio for the fundamental laser wavelengths 1 064 nm and 1 319 nm to obtain gain-matching and the approxlmate equal number of intracavity photons is very important. Here left facet of Nd:YAG is coated with 808 nm antireflection(AR), $T>95\%$; and 1 064 nm and 1 319 nm high reflection (HR) coatings are as all reflective mirrors; right facet with 1 064 nm/1 319 nm(AR), $T>98\%$; The concave surface of the output mirrors are coated with 1 319 nm HR, $R>99.9\%$, 588. 9 nm AR, $T>95\%$ and 1 064 nm partly transmission. Practically, it is difficult to control the precise reflection values of the output mirrors for wavelength of 1 064 nm. By experiments, when the output mirror with the transmission value of 2. 7% for 1 064 nm, the maximum output power of yellow-light 588. 9 nm is achieved. Two facets of LBO both coated with 1 319 nm/1 064 nm/588. 9 nm AR coatings.

Table 1 Comparision of three different CPM crystals for nonlinear frequency conversion

LBO crystal (nm)	Phase-matching angle θ_m/(°)	Orientation angle φ/(°)	effective nonlinear coefficient d_{eff}(pm/V)
532	90	11. 3	0. 832
660	85. 9	0	0. 818
588. 9	90	3. 4	0. 837

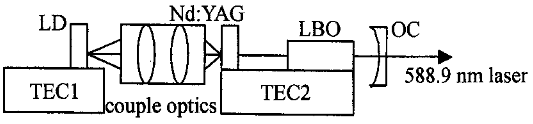

Fig. 2 The setup of LD-pumped yellow laser

In room temperature, by adjusting the current of LD, when the incident pump power is 390 mW, the IR laser output is observed without LBO crystal. Then the mirror is replaced with a yellow laser output mirror and the nonlinear crystal LBO is placed in the resonator, yellow-laser at 588. 9 nm is obtained when the current of LD is 410 mA. With the current of TEC1 and TEC2 increasing, the maximum SFM output power of 588. 9 nm is obtained with type-Ⅰ critical phase-matching LBO when the pumping power is 1. 8 W. After 808 nm, 1 064 nm and 1 319 nm laser are filtered, the yellow laser at

588. 9 nm output power is up to 62 mW. Fig. 3 shows the ratio of output power to incident pump power for dual-wavelength operation. It can be seen that the output power of both wavelengths increased monotonical as the incident pump power increased. The yellow laser output power as a function of incident pump power is shown in Fig. 4, it can be found as the pump power increased, the output power at 588. 9 nm rose corresponding, whereas in the rising process, the output power produced a little fluctuations, the output power decreased, but later the power became stable little by little. The gain competition between 1 064 nm and 1 319 nm laser results in the instability of the output power.

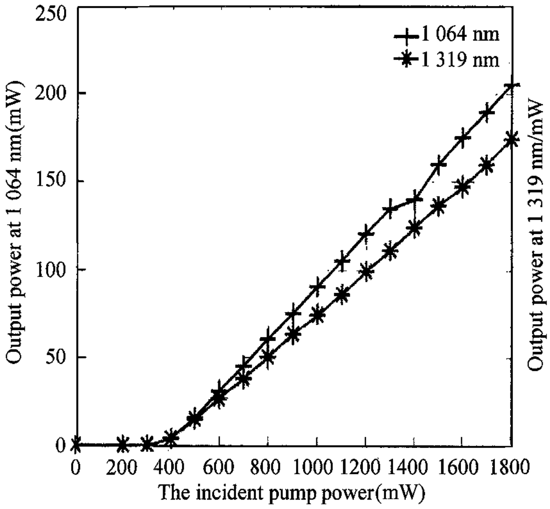

Fig. 3 The relative output power at 1 064 nm and 1 319 nm as a function of pump power

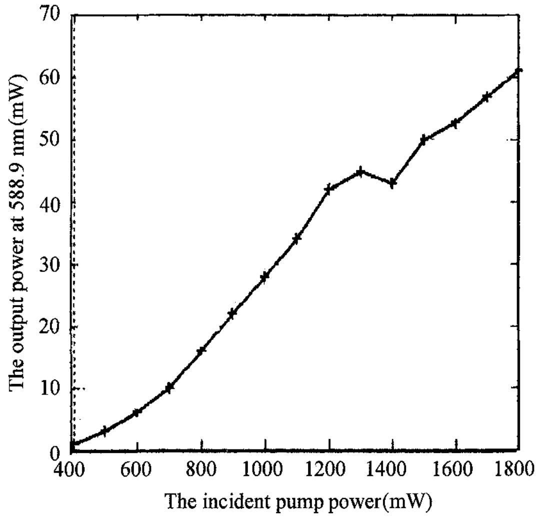

Fig. 4 The laser output power at 588. 9 nm as a function of pump power

When the other LBO crystal was used for intracavity frequency doubling, the green laser at 532 nm output power is 93 mW, and the red laser at 660 nm is up to 77 mW. The conclusion can be made that 1 064 nm and 1 319 nm fundamental lasers have good spatial, temporal overlap and gain matching. The otpical-to-optical conversion efficiency is up to 3. 4%. The power in stability in 24 h is better than ±2. 7%.

In summary, by film and resonator optimum designs, we have achieved good balance for the numbers of intracavity photons and gain matching between 1 064 nm and 1 319 nm lasers. Diode-end-pumped Nd: YAG laser that generates simultaneous CW laser at wavelengths of 1 064 nm and 1 319 nm is demonstrated. By use of type-I critical phase-matching LBO crystal intracavity sum-frequency-mixing, yellow laser output at 588. 9 nm CW is obtained.

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