Design of high energy, single frequency, all solid-state blue laser

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A high energy all-solid-state blue laser with wavelength of 455 nm is proposed, which can be used in laser communication underwater or in the differential absorption lidar (DIAL) system. Ti:sapphire crystal is suitable material and is pumped by the second harmonic generation (SHG) of Nd:YAG laser. The pumped laser of 1000 mJ, 10 Hz is used, and the output wavelength of Ti:sapphire resonator cavity is controlled by external injection seeding. Parameters of the resonator cavity of Ti:sapphire crystal is carefully calculated and optimized. Pulsed 455-nm blue laser exceeding 100 mJ is obtained through frequency-doubled Ti:sapphire laser.

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Blue-green laser is used widely in differential absorption lidar (DIAL) system, laser communication, ocean exploration and so on. In the applications, high energy, single frequency, and pulsed all solid-state laser at wavelength of ultraviolet (UV) or blue is a good candidate as a transmitter. This kind of laser can be realized from nonlinear output of an injection-seeded Ti:Sapphire laser. Output energy larger than 30 mJ from an injection-seeded, frequency tripled Ti:Sapphire laser was reported for an ozone DIAL[1−5].

Output of 455 nm, which is matched a Cs atomic filter to reduce background noise, is preferred in the laser communication system. The high energy is necessary for the high attenuation of sea water. The frequency-doubled Cr:LiSAF laser is one way to get this wavelength[5,6], but the power of laser diode to pump Cr:LiSAF crystal is limited. Frequency-mixed Nd:YAG laser and Ti:sapphire laser were also demonstrated to generate 455-nm laser[7], but the stability of frequency-mixing is poor in practical applications due to the rigorous overlap of two narrow pulse widths. In this paper, we propose an all-solid-state Ti:sapphire laser at blue wavelength in application of laser communication underwater. It is a frequency-doubled, all-solid-state 532 nm pumped injection-seeded Ti:Sapphire laser. The detailed design and the corresponding numerical simulation are presented.

Ti:sapphire crystal is a widely tunable crystal to generate laser output from red to near infrared region. The stimulated emission cross-section of Ti:sapphire crystal at 910 nm is higher than that of Cr:LiSAF crystal, and it can be efficiently pumped by mature frequency-doubled Nd:YAG laser. Frequency-doubling of 910-nm Ti:sapphire laser is a feasible method to get high efficiency, narrow pulse-width 455-nm laser output. It will be more compact and stable due to all solid-state and only frequency doubling configuration. Figure 1 is the outline of the proposed blue laser based on Ti:sapphire crystal.

The laser is designed to generate 910-nm laser of more than 200 mJ with a pulse-width of about 20 ns under pumped energy of 1000 mJ at 532 nm. The repetition rate is 10 Hz at present. The pulse energy of 455-nm laser is over 100 mJ after frequency doubling. Single frequency is realized by the techniques of ring cavity and injection seeding.

Detailed configuration of Ti:Sapphire cavity is illustrated in Fig. 2. Two Ti:sapphire crystals are used in the laser system. The oscillate wavelength and line width of the Ti:sapphire resonator cavity are controlled by external injection seeding. Compared with linear resonator cavity, a ring cavity is chosen owing to the performance of reducing linewidth more conveniently. The Ti:Sapphire laser system is implemented in gain-guided oscillator similar to the Refs. [8, 9]. The pump beam is divided equally to pump the crystals into two directions. The laser is four mirrors ring cavity. All mirrors are flat mirror. The lengths of AB and CD are 280 mm in order to separate the pump beams and the oscillate beam at the position of mirror M1 or M2.

The damage threshold is 8−10 J/cm^2 for Ti:sapphire crystal at 532 nm. The pump energy density in this laser is controlled at half of the damage threshold. For the pump energy of 1 J with pulse width of 10 ns, the pumping beam diameter at crystal surface should be at least 3.6 mm and the pump power density in the crystal is about 491.5 MW/cm^2. If the spatial beam of pump laser is Gaussian, the Ti:sapphire laser can be taken as a gain

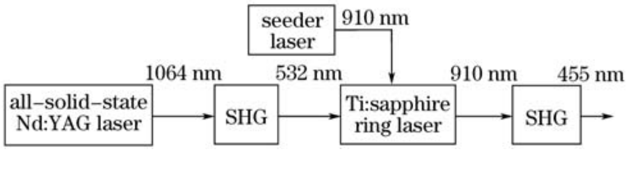

Fig. 1. Outline of 455-nm blue laser based on Ti:sapphire crystal.

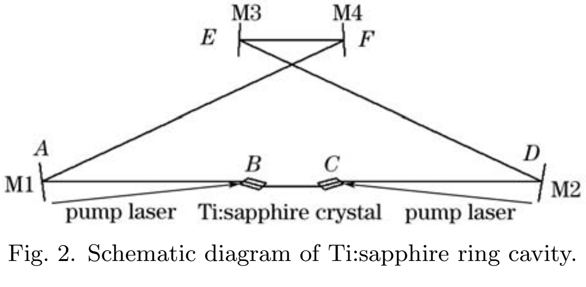

Fig. 2. Schematic diagram of Ti:sapphire ring cavity.

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guide with Gaussian aperture w_{g}[8]. The Fresnel number of the cavity is

$$N_{\mathrm{g}} = w_{\mathrm{g}}/\lambda d, \quad w_{\mathrm{g}} = w_{\mathrm{p}}/\sqrt{g_0}, \tag{1}$$

where, g_0 is the small signal intensity gain, w_{p} is the pump beam size at l/e in amplitude in the gain medium. The radius w_{l} at l/e in amplitude of the TEM$_{00}$ mode is then given by

$$w_{\mathrm{l}}^2 = w_{\mathrm{p}}\sqrt{\frac{2\lambda_0 d}{\pi g_0}}. \tag{2}$$

The beam size can be enlarge when higher pumping energy is radiated in the crystal, therefore higher energy can be obtained from Ti:sapphire laser. The life time of up energy level of Ti:sapphire crystal is 3.2 μs and the pump pulse is far shorter, so the output performance can be approximately calculated as a Q-switched laser. The output energy of the laser can be calculated as

$$E = \frac{h\nu A}{2\sigma\gamma}\ln\left(\frac{1}{R}\right)\ln\left(\frac{n_{\mathrm{i}}}{n_{\mathrm{f}}}\right), \tag{3}$$

where $h\nu$ is the photon energy, A is the effective beam cross section, $A = \pi w_{\mathrm{l}}^2$. The relationship between the initial inverse population density n_{i} and the finial inverse population density n_{f} is

$$n_{\mathrm{i}} - n_{\mathrm{f}} = n_{\mathrm{t}}\ln\left(\frac{n_{\mathrm{i}}}{n_{\mathrm{f}}}\right), \tag{4}$$

where n_{t} is the threshold inverted population density and $n_{\mathrm{t}} = \frac{1}{2\sigma l}\left(\ln\left(\frac{1}{R}\right) + L\right)$.

The pulse width is

$$\Delta t_{\mathrm{p}} = \tau_{\mathrm{c}}\frac{n_{\mathrm{i}} - n_{\mathrm{f}}}{n_{\mathrm{i}} - n_{\mathrm{t}}\left(1 + \ln\left(n_{\mathrm{i}}/n_{\mathrm{t}}\right)\right)}. \tag{5}$$

The output characteristic of the Ti:sapphire laser corresponding to various pump power densities can be calculated. In order to calculate the characteristic of the resonator cavity, the cavity length is first assumed to be 1500 mm. Table 1 lists the parameters for laser specification's calculation. Through calculation, the threshold pump pulse energy of 156.9 MW/cm^2 is achieved.

Figure 3 indicates the output laser pulse-energy at various pump power densities. It can be seen that, when the pump beam size and cavity length is fixed, the output laser pulse energy increases with the pump power density.

Table 1. Parameters Used in Calculation

Laser Wavelength	910 nm
Pump Laser Wavelength	532 nm
Effective Stimulated Emission Cross-Section	$\sim 1.25 \times 10^{-19}$ cm^2
Fluorescence Life time	3.2 μs
Ti^{3+} Concentration	3.33×10^{19} cm^{-3}
Pulse Width of Pump Beam	10 ns
Diameter of Pump Beam	3.6 mm
Cavity Length	1500 mm

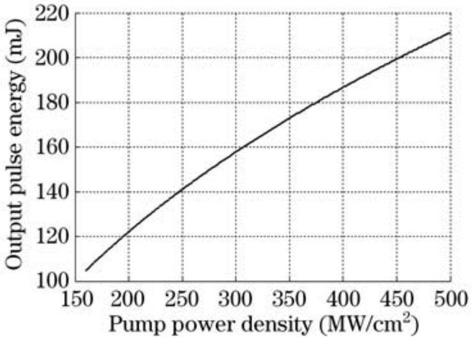

Fig. 3. Output pulse energy of Ti:sapphire laser versus pump power density.

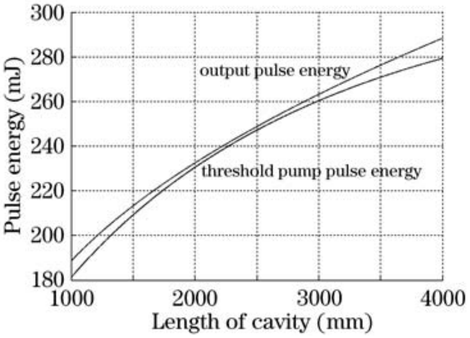

Fig. 4. Output pulse energy and threshold pump pulse energy versus Ti:sapphire resonant cavity length.

Figure 4 shows the output laser pulse energy at various cavity lengths when the pump beam diameter is 3.6 mm and the pump pulse energy is 1 J. From Fig. 4, it can be seen that the output pulse energy also increases with the cavity length. When the cavity length exceeds 1300 mm, the optical-optical efficiency from 532 nm pump laser to Ti:sapphire laser is more than 20%. Also, the resonate beam radius increases with the pump beam radius[8,9], so that higher output energy can be generated when the pump energy is higher.

The pulse width of Ti:sapphire laser can be calculated by Eq. 5. Figure 5 indicates the relationship between the cavity length and the output laser pulse. When the cavity is longer, the output laser pulse width increases. In order to assure the output laser pulse width no longer than 20 ns, the cavity length cannot increase excessively, although longer cavity can obtain higher output pulse energy at certain pump pulse energy. The cavity length can be selected as 1600 mm and Table 2 lists the design results of the Ti:sapphire resonator cavity.

According to the rate equations of Ti:sapphire laser, relationship between the output pulse and the pump beam

Table 2. Designed Results of Ti:Sapphire Resonator Cavity

Laser Wavelength	910 nm
Cavity Length	1600 nm
Threshold of Pump Energy	216.0 mJ per pulse
Pump Energy	1000 mJ per pulse
Pulse Energy of Output Laser	212.3 mJ per pulse
Pulse Width of Output Laser	17.0 ns
Optimum Output Ratio of the Output Mirror	48.1%

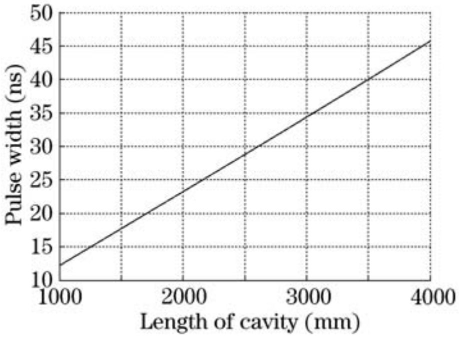

Fig. 5. Pulse width of the output laser versus Ti:sapphire resonant cavity length.

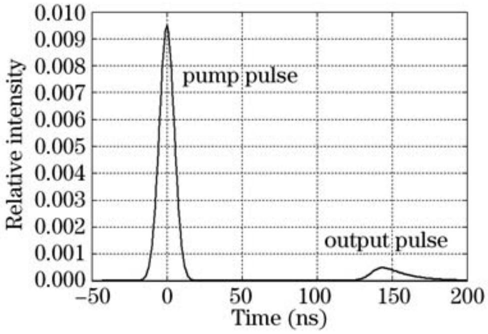

Fig. 6. Build-up time of Ti:sapphire under pump energy of 1 J and pulse width of 10 ns.

can be obtained as

$$\mathrm{d}n/\mathrm{d}t = \omega_\mathrm{p} - \sigma\nu N_0 n\varphi - n/\tau_0, \qquad (6)$$

$$\mathrm{d}\varphi/\mathrm{d}t = \sigma\nu l/LN_0 n\varphi - \varphi/\tau_R, \qquad (7)$$

where τ_0 and τ_R are the spontaneous radiation lifetime and the photon lifetime determined by the loss of the cavity respectively, n is the normalized inverted population density and φ is the normalized photon density of the cavity, ω_p is the pump pulse frequency, N_0 is the Ti:$^{3+}$ doping concentration, ν is the light velocity in the crystal, l and L are the lengths of gain medium and the cavity.

The above dynamic model can be solved by four-order Runge-Kutta integration method. When the pump pulse energy is 1 J and the Ti:sapphire resonator cavity length is 1600 mm, the time delay between the pump pulse and the output pulse can be indicated in Fig. 6 and the time delay is about 140 ns.

The 910 nm laser from the Ti:sapphire resonator cavity will be frequency doubled by nonlinear optical crystals. $\mathrm{LiB_3O_5}$ (LBO) is suitable to frequency-doubled Ti:sapphire laser[1−4]. LBO crystal has wide acceptable angle and small walk-off angle. It is widely used in practice and has obtained satisfactory results. The second harmonic generation (SHG) simulation taking into account the spatial and temporal profile of the incident fundamental beam is carried out assuming the triangle waveform which has the 17-ns pulse width and Gaussian beam profile which has 2.54-mm spot size as calculated in the above procedure. Figure 7 shows the predicted performance of the SHG for LBO crystal. An frequency conversion efficiency of more than 50% is expected at proper crystals lengths assuming various phase mismatchs of $\Delta k = 0$, 0.5, and 1.5. Then, 455-nm laser of pulse energy exceeding 100 mJ can be generated.

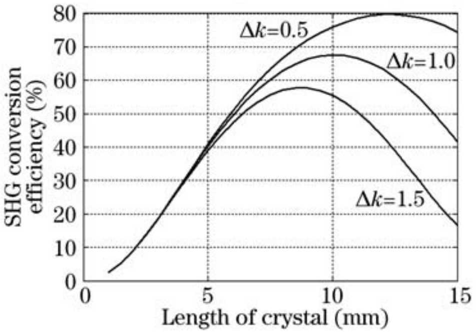

Fig. 7. SHG conversion efficiency of 910-nm laser versus length of LBO crystals.

For future laser communication underwater, a high energy, narrow-pulse-width, high efficiency, all-solid-state blue light laser based on Ti:sapphire crystal is designed. The corresponding numerical simulation is conducted. The pumped 532-nm laser with 1000 mJ at 10 Hz is achieved. A Ti:sapphire laser pumped by the green laser will be tuned to 910 nm by an injection seeder and the output energy is to be more than 200 mJ per pulse when pumped by 1000-mJ green laser. Then, frequency doubled by LBO crystal of proper length, more than 100 mJ blue laser of 455 nm with a repetition rate of 10 Hz is expected to be generated. This laser system is now under development.

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References

1. S. Chen, L. B. Petway, B. L. Meadows, K. A. Elsayed, W. D. Marsh, W. C. Edwards, and J. C. Barnes, in *Proceeding of CLEO 2001* 506 (2001).
2. K. A. Elsayed and S. Chen, Proc. SPIE **4630,** 89 (2002).
3. K. A. Elsayed, R. J. DeYoung, and L. B. Petway, Appl. Opt. **42,** 6650 (2003).
4. K. A. Elsayed, S. Chen, and L. B. Petway, Appl. Opt. **41,** 2734 (2002).
5. P. Laperle, K. J. Snell, A. Chandonnet, P. Galameau, and R. Valle, Appl. Opt. **36,** 5053 (1997).
6. L. Liu and K. Nagashima, Opt. Eng. **38,** 1789 (1999).
7. A. J. W. Brown, C. H. Fisher, and K. Kangas, Opt. Lett. **18,** 1177 (1993).
8. F. Salin and J. Squier, Opt. Lett. **17,** 1352 (1992).
9. F. Estable, E. Mottay, and F. Salin, Opt. Lett. **18,** 711 (1993).