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Broadband and rapid tuning of an all-solid-state single-frequency Nd:YVO_4 laser

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ABSTRACT A diode-pumped tunable single-frequency Nd:YVO_4 laser has been built. The laser incorporates a $LiNbO_3$ etalon (LE) as a coarse tuning element and a $LiNbO_3$ crystal (LC) as a fine tuning element to obtain broadband, rapid tuning. More than 480 mW of output power has been obtained from the tunable laser with frequency tuning range of 17.2 GHz and the tuning response time of 10 ns.

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1 Introduction

Frequency-tunable all-solid-state lasers are of interest for a wide field of applications, e.g., scientific research, medicine, measurement and testing techniques, and communication. Broadband rapid tuning of the diode-pumped Nd laser has been achieved by controlling the laser cavity length using piezo-electric [1–3] and electro-optic effect [4]. Using above techniques, the laser frequency can be scanned over a single longitudinal mode, and in order to obtain the frequency scan ranges of 1 GHz the miniature resonators have to be built. Monolithic structures [5], in particular, can be very short and offer superior frequency stability. However, single-frequency operation of such lasers is limited to low powers. Okhapkin et al. [6, 7] reported two tunable lasers tuned by KTP crystal temperature, but the tuning speed is limited owing to the temperature tuning. High power and broadband rapid tuning of lasers [8, 9] have been achieved by using an intracavity etalon that is mounted on a galvanometer as a coarse tuning element and a cavity mirror mounted on the piezo-electric as a fine tuning element. But the reliability, repeatability and tuning speed of the laser are limited by the mechanical parts of the galvanometer, which the tuning speed of the laser only reaches the level of microsecond.

In this paper, we designed an approach to realize a broadband and rapid tuning laser. The main features are a ring resonator employed in our experiment to enforce a single frequency laser, a $LiNbO_3$ etalon (LE) to provide broadband tuning, and a $LiNbO_3$ crystal (LC) to provide continuous tuning. Frequency tuning over the laser gain spectrum, covering many longitudinal modes, is fulfilled by controlling the voltage of the LE. Frequency control within a single longitudinal mode is obtained by adjusting the voltage of the LC, which is used as an equipment of adjusting the optical path. Electronic tuning sets that are immovable were engaged instead of mechanical parts, which improved further robust and tuning speed of the laser. As a result, only one laser can we gain high output power, broadband and high speed tuning at the same time. In our experiment, more than 480 mW of output power has been obtained from a single-frequency tunable laser, which has a frequency tuning range of 17.2 GHz and tuning response time of 10 ns.

2 Experimental designs

The tunable laser configuration is shown in Fig. 1. A figure-eight-shaped ring resonator formed by four mirrors is designed. The input coupler M1 is a plane mirror with high reflection at 1.064 μm and antireflection at 808 nm; the cavity mirrors M2 and M3 are plano-concave mirrors with high reflection at 1.064 μm and radius of 50 mm; the output coupler M4 is a plane mirror with the reflection of 95% at 1.064 μm. The length of the laser cavity is 350 mm. A laser diode is used as pump source. Laser-diode beam is focused to the Nd:YVO_4 crystal by the telescope system with transmission efficiency of 94%. The size and the Nd-doping concentrations of the a-cut Nd:YVO_4 crystal are 3 mm × 3 mm × 5 mm and 0.5 at. %, respectively. Both end faces of Nd:YVO_4 crystal are antireflection coated at 1.064 μm and 808 nm. An optical-diode containing a TGG crystal and a half-wave plate is used to enforce

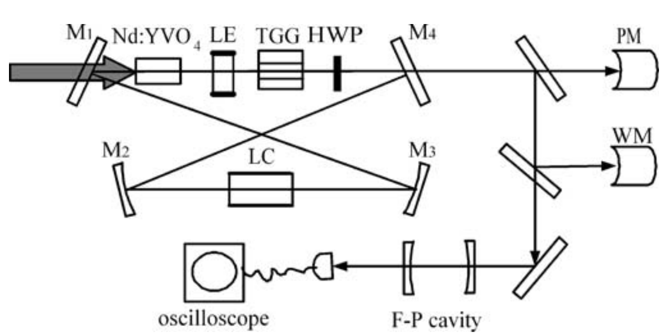

FIGURE 1 Experiment schematic of the tunable laser: LE – $LiNbO_3$ etalon, LC – $LiNbO_3$ crystal, HWP – half wave plate, PM – power meter, WM – wavelength meter

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the laser of unidirectional operation, whose function is eliminating the spatial hole and achieving the single-frequency operation. Without the LE and LC, the output power was about 1 W at 2.2 W of absorbed pump power. With the two $LiNbO_3$, the maximum output power was 510 mW and the minimum power was 480 mW over the tuning range. It is probable that the reduction in output power is due to inserting loss of the LE and the LC.

To obtain a broadband, rapid tuning laser, a $LiNbO_3$ etalon (LE) and a $LiNbO_3$ crystal (LC) are utilized inside the laser cavity as coarse tuning element and fine tuning element, respectively. In order to get the strongest linear electro-optic effect, the LE and LC form the x-axis cutting with two electrodes in the z-direction. The polarization of the light is parallel to the optic axis of the crystal (e-wave), and the propagation of the light is along x-direction in the crystal. The LE is designed so that the size is $2 \times 2 \times 1\ \mathrm{mm}^3$ (where the 1-mm length is along the x-axis) and two end faces are uncoated. The free spectrum range (FSR) of the LE is 69.6 GHz and the finesse of LE is about 1.3. When the electric field of $\pm 2000\ \mathrm{V/mm}$ is applied on the electrodes of LE, the change of the refractive index can tune the laser frequency coarsely over 70 GHz. The LC is designed so that the size is $2 \times 2 \times 10\ \mathrm{mm}^3$ (where the 10-mm length is along the x-axis) and two end faces are antireflection coated at 1064 nm and unparallel to eliminate the etalon effect. The angle between the two end faces is 1-deg, which is enough to eliminate the etalon effect in our experiment. When the electric field of $\pm 390\ \mathrm{V/mm}$ is applied on the electrodes of LC, the laser can be fine tuned over one FSR (860 MHz) of laser cavity. In the y-direction of LE and LC, grooves which are used as the electrodes were cut into the copper and filled with polyimide to improve the acoustic-damping properties [4] that can decrease undesired amplitude and frequency modulation.

The tuning speed of the laser is limited by the modulation speed of the $LiNbO_3$ and the cavity length. The frequency response of a laser whose length is modulated is well understood. Briefly, when a linear voltage ramp is applied, the frequency of the laser undergoes a series of steps whose spacing in time is the cavity round-trip time. When the voltage rise time is long compared with the cavity round-trip time, the modulation speed of two $LiNbO_3$ determine the response time. On the contrary, the cavity round-trip time is longer than the modulation speed, the laser cavity length determine the response time. The small size of our modulator crystal gives low capacitance and good high-frequency response, important for extending the electro-optic tuning to higher frequency. Maximum modulation speed can be expressed by $f_\mathrm{m} = c/2Ln$ (where n is index of extraordinary rays of $LiNbO_3$ (2.156 for 1064 nm), L is length of modulator, and c is the vacuum velocity of light). For the LE ($L = 1$ mm), the LC ($L = 10$ mm) and the laser cavity length of 350 mm, it can be predicted that the tuning response time should be 0.02 ns, 0.2 ns and 1 ns, respectively. So the tuning response time of the laser is 1 ns. Another advantage of using electro-optical modulator as frequency tuning element is that the tuning response time is only related to modulator and not to the tuning range.

3 Experimental results and results analysis

When the two $LiNbO_3$ crystals are inserted in the laser cavity, the maximum output power of single frequency laser is 510 mW. A home-made confocal interferometer at 1064 nm with the finesse of 380 and FSR of 1.5 GHz is used to monitor fine tuning of laser frequency. A wavelength meter (Coherent Inc, model wavelength TM) whose precision is 0.001 nm is used to measure the central wavelength of the laser.

When the electric field was applied on the electrodes of the LE and LC, the frequency of the laser can be coarsely and finely tuned, respectively. The electric field is supplied by a direct current high voltage source, with bipolar power supplies as high as ± 1000 V can be safely applied on the electrodes of the crystal. Figure 2 is the coarse tuning of laser versus the voltage applied on the LE. It is shown that the tuning range of the laser is 0.06 nm (17.2 GHz), and the tuning

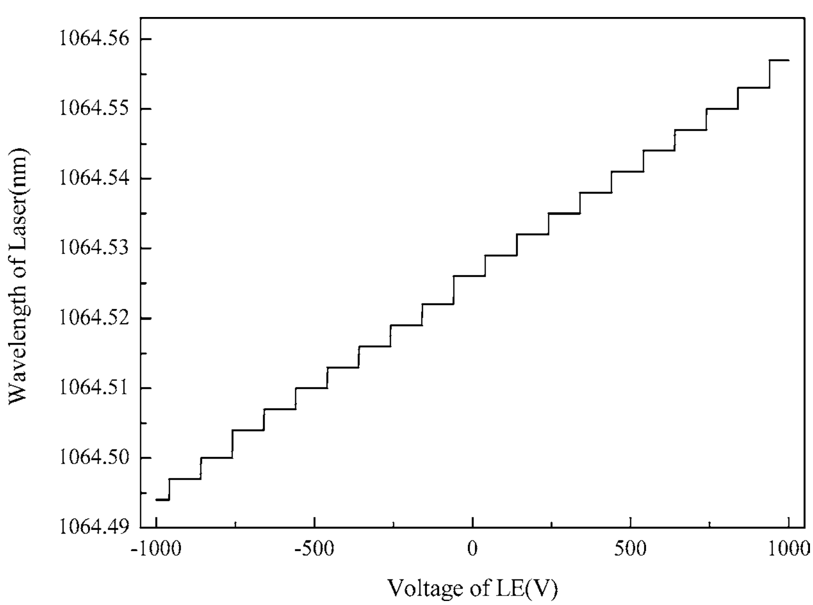

FIGURE 2 Coarse tuning of laser vs. the voltage applied on the LE

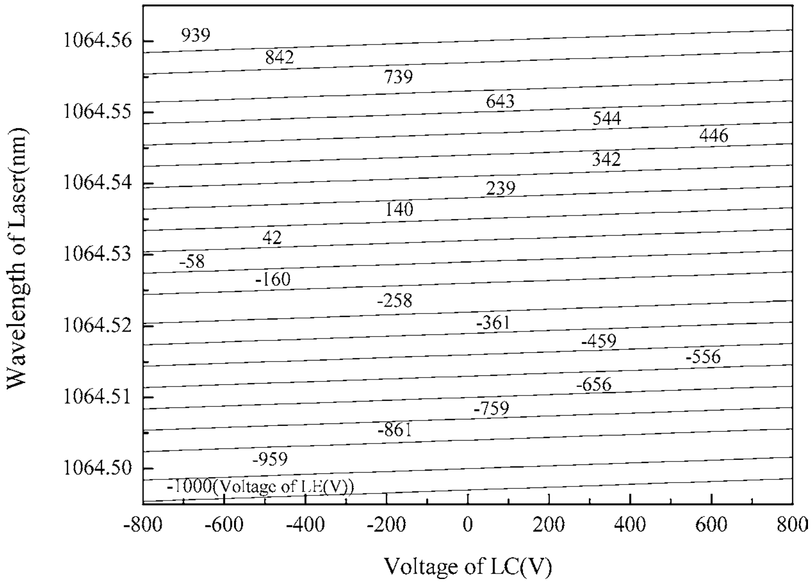

FIGURE 3 Fine tuning of laser vs. the voltage applied on the LC at different voltages applied on the LE

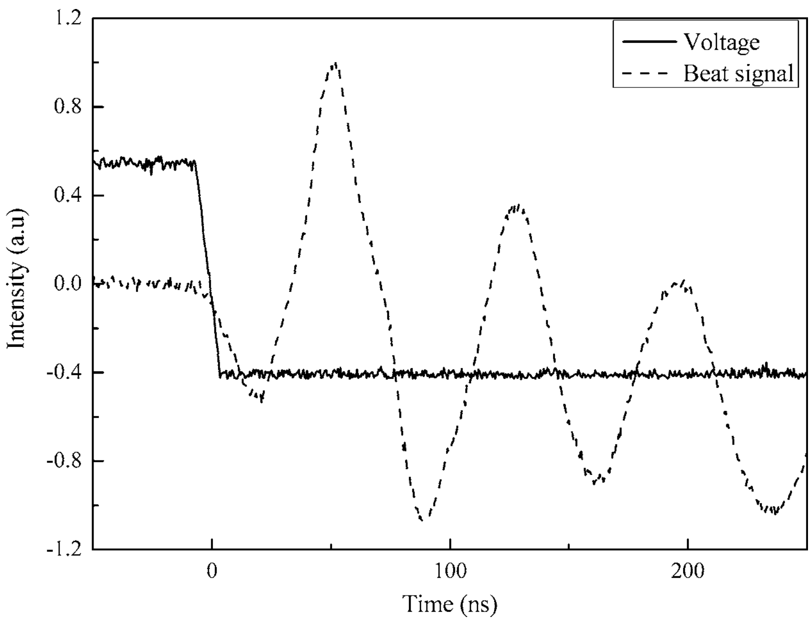

FIGURE 4 Oscilloscope traces of the heterodyne beat signal and voltage step. *Solid curve*: voltage applied on the LC. *Dashed curve*: beat signal

is linear over the entire voltage. When the voltage applied on the LE is changed at about 100 V, the frequency of the laser shift suddenly by 860 MHz (the FSR of the laser cavity). The mode hope also can be observed by the confocal interferometer. At interval of the longitudinal mode hopping, the change of the voltage on the LE did only adjust the cavity length. Because the length of ring laser cavity is much larger than that of the LE, the frequency tuning is very small (approximately 5 MHz) that can not be observed by wavelength meter. Figure 3 is the fine tuning of laser versus the voltage applied on the LC at different voltages applied on the LE. It can be seen that the laser can be fine tuned over one FSR (860 MHz) of the laser cavity when the voltage of ± 780 V applied on the LC, which is in good agreement with the theoretical prediction.

To measure the tuning response time of the laser, another constant-frequency laser of the same design is used as a standard of frequency reference and a 50 V voltage step with a 10 ns rise time applied on the LC. The output beams of the two lasers are incident on an InGaAs photodiode with the response time of 0.6 ns. The resulting heterodyne beat signal is monitored by a 600-MHz oscilloscope that shown in Fig. 4, in which the changes of the beat signal indicate those of the laser frequency. It can be found that the response time of the voltage is 10 ns from Fig. 4, and the observed frequency tuning response time is consistent with the response time of the voltage. Thus, the response time of our tunable laser responds to an applied voltage in a time less than 10 ns. Then, we measure the response time at different voltage steps, it is found that the frequency tuning response time is independent of the value of the voltage step applied on the LC.

4 Conclusion

In summary, a broadband and rapid continuous tuning single frequency laser pumped by a laser-diode is

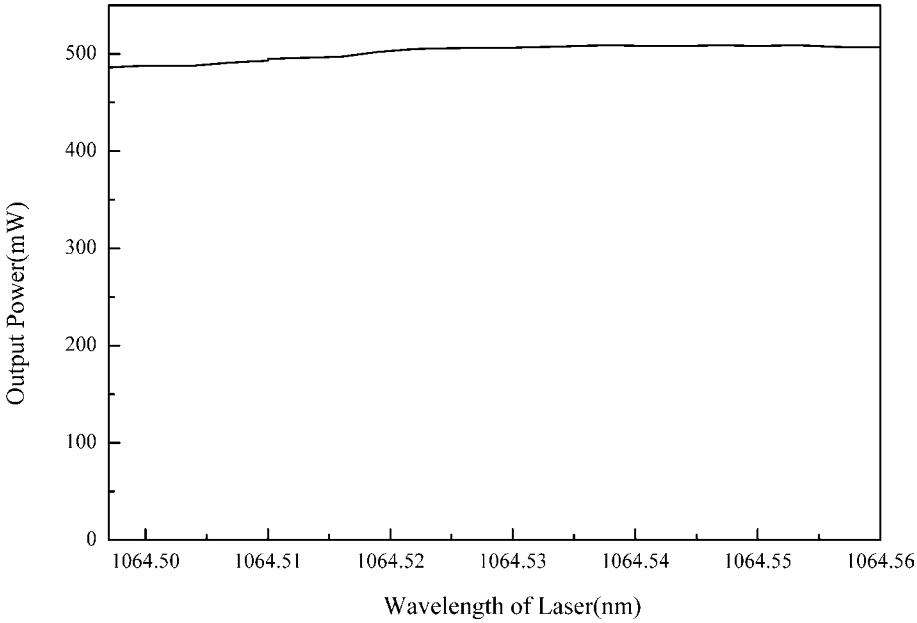

FIGURE 5 Laser output power vs. wavelength

obtained by adjusting the voltage applied on the LE as a coarse tuning and that on the LC as a fine tuning. The frequency tuning range is 17.2 GHz and the tuning response time is 10 ns. More than 480 mW of output power (maximum power of 510 mW) has been obtained from the tunable laser over all frequency tuning range (as shown in Fig. 5). Compared with former works, our laser achieves high output power, broadband and high speed tuning at the same time. According to the theoretical prediction, when the rise time of the voltage step is improved to less than 1 ns, the tuning response time of the laser can reach the order of ns.

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