# Experimental research on the stability and the multi-longitudinal mode interference of bidirectional outputs of LD-pumped solid-state ring laser

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## Abstract

This paper reports an experimental research on the stability of bidirectional outputs and multi-longitudinal mode interference of laser diode end-pumped Nd:$YVO_4$ solid-state ring laser (DPSSL). The bidirectional, multi-longitudinal and $TEM_{00}$ mode continuous wave outputs are obtained and the output powers are measured and their stabilities are analyzed respectively. The spectral characteristic of the outputs is measured. The interfering pattern of the bidirectional longitudinal mode outputs is obtained and analyzed in the condition of the ring cavity with rotation velocity. The movement of the interfering fringe of the multi-longitudinal modes is very sensitive to the deformation of the setup base and the fluctuation of the intracavity air, but is stationary or randomly dithers when the stage is rotating.

**Keywords: laser stability, multi-longitudinal mode, optical interference, bidirectional ring laser, rotation sensor, Nd:$YVO_4$**

## 1. Introduction

Since laser diode pumped Nd laser material solid state laser (DPSSL) has the advantage of a wide range output power and high coupling efficiency for its good spectral match between the emission spectrum of pump beam and absorption spectrum of laser medium[1], DPSSL is applied in many industrial fields. Solid state ring lasers have been exploited to attain unidirectional single frequency laser. Nonplanar single-frequency solid state ring laser was first reported by Kane and Byer[2] in 1985. T. Day reported the 30Hz linewidth of single-frequency unidirectional ring laser[3]. The expected quantum-limited linewidth of 1Hz for 1mW of output power is predicted by Schawlow-Townes equation[4]. In 1988, Byer predicted that a ring laser with quantum noise-limited linewidth could sense rotation[5] at 1 $hour^{-1}$ $(Hz)^{-1/2}$. Some patents of solid state ring laser as optical gyro were also reported[6,7] . J-C Diels[8, 9, 10] established a mode-locked ring laser gyroscope with absence of dead band using MQW absorber. Their experiment showed that controlling the meet position of the two directional could obtain zero lock-in threshold by optimum design of the cavity. continuous wave single-mode monolithic unidirectional ring lasers and mode locking pulse ring lasers are mainly presented, but bidirectional continuous wave solid state ring

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laser used as rotation sensor has not been presented because it is commonly considered that gain competition between the counter-propagation oscillation has precluded the use of homogeneous broadening active medium in ring laser gyro.The research motivation of this paper is to study the stability and the multi-longitudinal mode interference of bidirectional outputs of LD-pumped solid-state ring laser using homogeneous broadening active medium by experimental method.

## 2. Ring laser design

Comparing to the conventional 1 at.% Nd:YAG whose absorption cross-section is about $2.8\times10^{-19}$ $cm^2$, the π -absorption cross-section of transition $^4I_{9/2} \rightarrow {}^4I_{5/2}$ at 808.4 nm of $Nd:YVO_4$ is about 3.5-4 times laser larger. The width of this absorption is large enough to enable a better use of LD pump, especially for $TEM_{00}$ emission[11]. In the setup, laser crystal $Nd:YVO_4$ is exploited as gain medium.

End-pumped geometry is considered because this pump method can provide the DPSSL with the best volume mode match between LD pump beam and resonating beam in ring cavity. As shown in Fig.1, the ring laser resonator is a closed X-shape 4-mirror nonplane ring cavity in which $Nd:YVO_4$ crystal is exploited as gain medium that is longitudinally pumped by a 2W laser diode through a collimating lens system with which the highly divergent pump beam is collimated to focus inside the crystal sample.

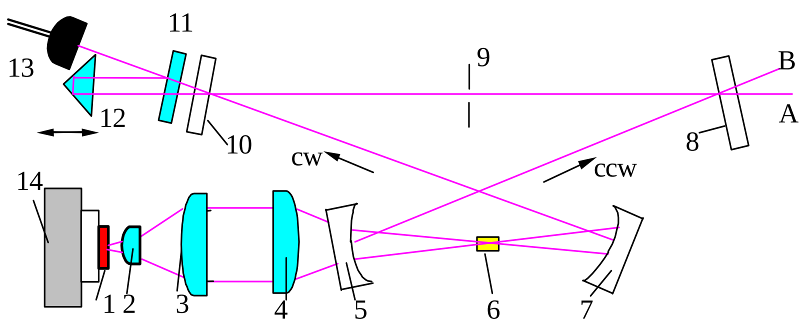



Fig.1. Schematic diagram of the DPSSL. The ring cavity consists of the curved mirrors (5, 7) and flat mirrors (8,10). The crystal mounted on the focus of mirror (5) and mirror (7) is pumped by a LD through a collimating lens system which is composed of the lenses (2, 3, 4). The laser beams (CW, CCW) output from the mirror (10) interfere on CCD camera through the prism (12) and the beam splitter (11). In order to obtain $TEM_{00}$, A diaphragm (9) is mounted in the cavity.

The ring cavity consists of two curved mirrors (antireflection coating at 808 nm, high reflection at 1064 nm) and two flat mirrors. The two mirrors have the curvature radius of 100mm and are mounted 100mm apart symmetrically. One of the two mirrors (10) is 70% reflecting at 1064nm as the output coupler(OC) for laser, the other has high reflectivity coating. Packed with In foil，the laser medium is mounted in a copper slot and located at the confocus of the two curved mirrors. It has dual coatings on the pumping side (antireflection coating at 808 nm and 1064 nm) and the other side has antireflection coating at 1064 nm.

The length of one round optical trip of ring cavity is 0.505m. In order to obtain $TEM_{00}$, A diaphragm (K) is mounted in the cavity. In the ring resonator, there are two counter propagating beams, one is clockwise (CW) beam, the other is counter clockwise (CCW) beam. The two beams output from a cavity mirror (10) and interfere on the photon detector (13) or CCD camera with each other through a certain optical delay path which includes a 50% transmission beam splitter and a prism (12). To avoid the influence of 808nm when the out powers are measured, two narrow-bandwidth light filters (HB optical 1064nm/10nm) are set to point A and B before powermeter. The whole solid state laser system is mounted on a rotation stage which can be driven by hand or by motor at a certain rotation velocity.

## 3. Experiment and analyses

In the experiment, the laser crystal was doped $Nd^{3+}$ 0.5%, its size is $3\times3\times5$mm. Laser diode is attached to a semiconductor cooler which mounts to an aluminum radiator and the temperature of laser diode is stabilized at $25^{o}C$ by the cooler feedback control system. The maximum current of laser diode is up to 2.8A with 2 W power output of laser diode.

The bidirectional, multi-longitudinal and $TEM_{00}$ mode continuous wave outputs are obtained and detected by CCD camera system and laser spectrum analyzer. In the experiment, the threshold of DPSSL is about 0.4W and the maximum output power is 0.7 mW. The O-O conversion efficiency is low because the pump beam focused into laser crystal is collimated by a lens and an object lens, not by an anamorphic prism. Fig.2 shows intension distribution of $TEM_{00}$ captured by CCD camera, and it has a top-hat profile, as shown fig.3. The peak of profile is flat for the signal saturation of CCD camera.

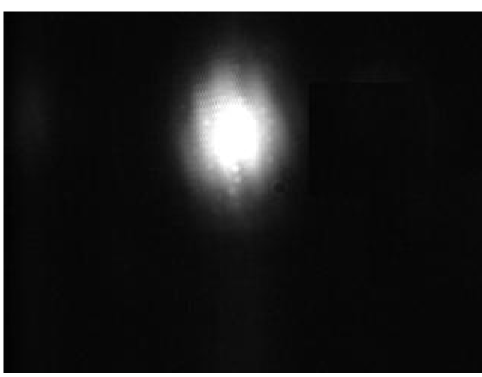


Fig.2 Intension distribution of $TEM_{00}$ captured by CCD camera

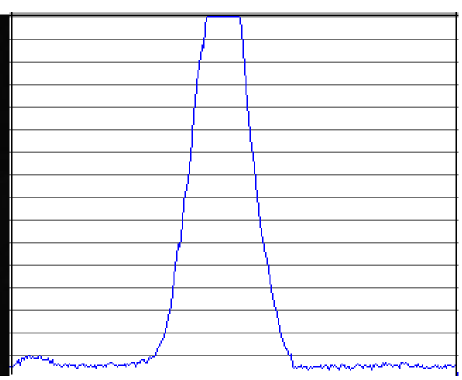


Fig.3 Cross section distribution of $TEM_{00}$.

The characteristics of multi-longitudinal modes, including the bandwidth, the longitudinal mode separation and mode distribution noise caused by optical power random distribution and mode competition is calculated and experimentally analyzed in order to study the factors which influence the single longitudinal mode resonation. Fig.4 is the laser spectrum detected by F-P laser spectrum analyzer whose finesse is more than 200 and the free spectral range is about 3.75GHz. The channel one (1) is the driving voltage of the F-P, and the channel two (2) is the signal of laser longitudinal mode spectrum. The separation of longitudinal modes is given by

$$\Delta \nu = \frac{c}{nl} \tag{1.1}$$

Where $l$ is the length of round trip of ring laser, $n$ is refractive index of intracavity air, $c$ is light speed.

For the ring laser with $l = 0.505m$ one obtains $\Delta \nu = 594MHz$ . Experimentally the separation of longitudinal modes is about 650MHz , as shown in Fig.4. There exists amplitude fluctuation of longitudinal mode, which is the result of gain competition of longitudinal modes. And longitudinal mode hops are observed in the ring cavity.

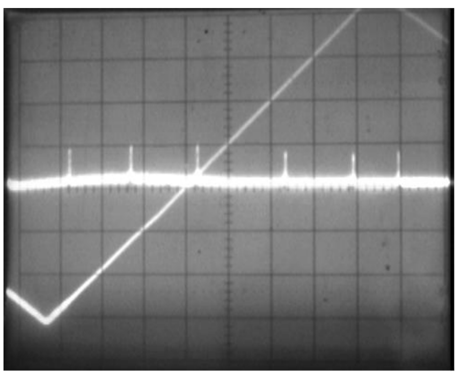
2 

Fig.4. laser longitudinal mode spectrum

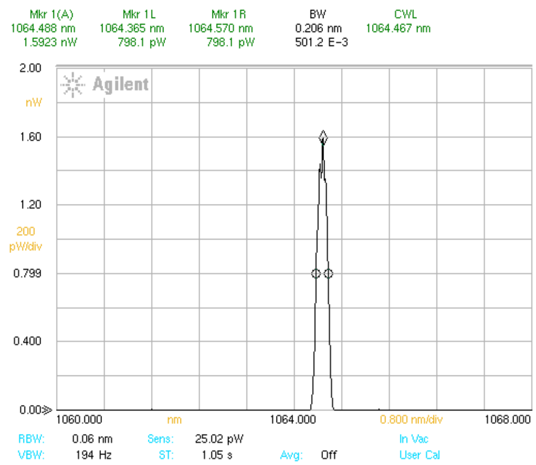



Fig.5 The laser spectrum detected by laser spectrum analyzer

The spectral characteristic of the outputs is measured, as shown in Fig.5. Fig.6 illustrates the central wavelength and the bandwidth of spectral change with the increase in pump power. When the central wavelength becomes lager, the bandwidth of spectral becomes broad accordingly. The changes of laser spectral attribute to wavelength change of LD, crystal thermal effect, etc. Advanced research is required to analyze the behavior of laser spectral in ring cavity.

The output powers are measured and their stabilities are analyzed respectively and relatively, as shown Fig.7 and Fig.8. With 1.0W pumping power, the average output power of CW beam is 16.9 uW and that of CCW beam is 7.8 uW. The power stability of CW beam and CCW beam is 0.4% and 5.5%, respectively. It is found that the output powers of the opposite direction beams from the output mirror (8) are not equal and very different from each other. The stability of the different power from CW beam and CCW beam is 5.4%. The explain is that different longitudinal modes are relative to certain gain curves with certain powers.

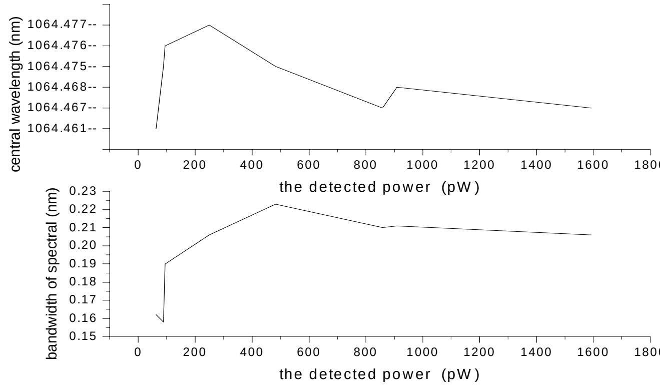



Fig.6 The central wavelength and the bandwidth of spectral change with the increase in pump power

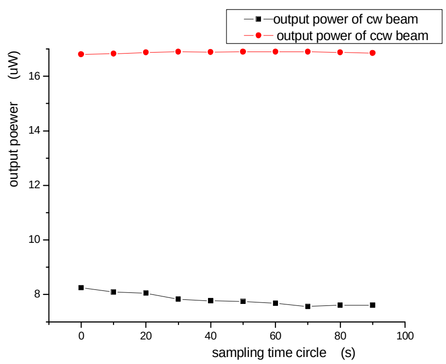



Fig.7 Output power of CW beam and CCW beam

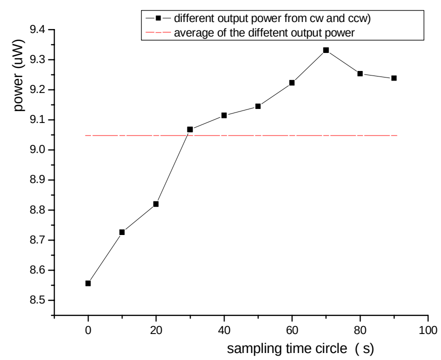



Fig.8 Different output power for CW beam and CCW beam

In the setup, one of the bidirectional beams interferes with the other on the photo detector with optical delay. The interfering pattern of the bidirectional longitudinal mode outputs is obtained by photo detector system and analyzed in the condition of the ring cavity with rotation velocity. Fig.9 is the interfering pattern of the two counter-rotating beams. It is shown that the movement of interfering fringe is very sensitive to the deformation of the setup base and the fluctuation of intracavity air. But the movement of the interfering fringe of the multi-longitudinal modes is stationary or randomly dithers whether the stage is rotating or not. This is because the linewidth of longitudinal mode is MHz magnitude, there exists mode lock-in effect between the frequency of CW beam and CCW beam within a certain rotation velocity. Also the longitudinal mode hops can cover up the Sagnac effect. And large amplitude noise due to longitudinal mode coupling may influence it. For solid state continuous wave ring laser used as an optical rotation sensor, it is necessary to insert intracavity elements such as etalon to eliminate the amplitude fluctuation, stabilize the frequency and narrow the mode linewidth down to Hz magnitude.

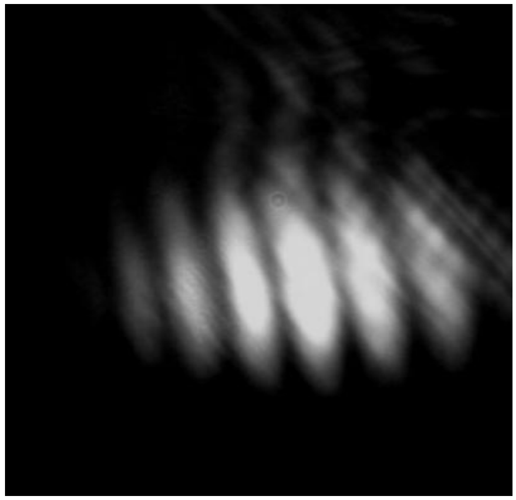


Fig.9 laser interfering pattern when the pump power is 0.50W

## 4. Conclusion

In summary, the characteristics of the multi-longitudinal and $TEM_{00}$ modes in the solid state bidirectional ring laser using homogeneous broadening active medium is studied. The central wavelength and the bandwidth of spectral change with the increase in pump power. The output powers of bidirectional beam are different from each other. The power stability of CW beam and CCW laser beam outputs is 0.4% and 5.5%, respectively. Amplitude fluctuation and longitudinal mode hops are observed and the movement of the interfering fringe of the multi-longitudinal modes is stationary or randomly dithers when the stage is rotating, which shows that it is necessary to insert mode selecting elements to achieve single longitudinal mode and eliminate the amplitude fluctuation, stabilize the frequency and narrow the mode linewidth down to Hz magnitude for solid state ring laser used as an optical rotation sensor.

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