Laser Original**Characteristics of an Astigmatically Compensated****Ti: Al₂O₃ Ring Laser****Tai Hyun YOON*, Gyu Ug KIM*, Jae Heung JO* and Yong Pyung KIM***

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An unidirectional output power of over 260 mW has been obtained at 790 nm from a Ti : Al₂O₃ ring laser pumped by all lines 5.6 W of an Ar⁺ laser. Astigmatism generated in the cavity by a 3-cm long laser crystal cut at Brewster angle was compensated. The cavity modes of the ring resonator were analyzed to obtain the optimum geometry of the Ti : Al₂O₃ ring laser cavity.

Key Words : Ti : Al₂O₃ ring laser, Cavity mode analysis, Astigmatism compensation, Unidirectional oscillation, Tunable laser.

1. Introduction

Tunable ring lasers are very useful in many areas of physics and chemistry, in particular for the high resolution spectroscopy and short pulse generation^{1,2)}. The Ti : Al₂O₃ (Sapphire) laser is one of the prominent candidates in this area, because it has very large tuning range in the near infrared of the spectrum. Pulsed laser operation has been demonstrated between 670 and 1020 nm³⁾, and continuous operation of the Ti : Sapphire laser pumped by Ar⁺ laser has shown as large as 2 W of output power and the tuning range from 680 to 1100 nm^{4,5)}.

Ti : Al₂O₃ laser has a considerable advantages over infrared dye lasers for the aspect of frequency stabilization to use in the high resolution spectroscopy, because it is free from the problem of hydrodynamical instabilities within the dye jet, which gives rise to frequency jitter in the dye laser output. For and a single etalon operates in a single axial example a Ti : Al₂O₃ ring

laser with a Lyot filter mode with an root-mean-square (rms) frequency jitter of 2 MHz⁶⁾, whereas a Lyot filter and two etalons are required to make a ring dye laser operate in a single mode with an rms frequency jitter of few 10 MHz⁷⁾. In addition, Ti : Al₂O₃ laser has homogeneously broadened gain medium, it can produce high single frequency power. A unidirectional ring cavity has been used to obtain stable single frequency operation with good beam quality. Unidirectional operation of a ring laser eliminates spatial hole burning induced by the standing wave field pattern within the gain medium^{6,8)} which makes single frequency operation easy.

Wassen et al.¹⁾, has constructed a Ti : Al₂O₃ unidirectional ring laser for high-resolution spectroscopy in atomic hydrogen and has obtained an output power of 1 W at 915 nm in a single axial mode with 10 W pump power. The frequency stability of this laser was 1 kHz rms with respect to locking etalon, which is compara-

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ble to the frequency stability of the dye laser stabilized to a stable reference cavity through a fast phase modulator inserted in the ring cavity⁹⁾.

In order to utilize the advantages of the Ti : Al₂O₃ ring laser we should first know the behaviors of the cavity modes and the complete compensation of the astigmatism generated in the cavity which influences the stable oscillation of the cavity mode. But there are no reports on the cavity mode analysis for the Ti : Al₂O₃ ring laser and compensation methods of the astigmatism generated by somewhat long laser rod (3 cm) compared to the thin dye jet in the laser cavity⁷⁾. In this paper we report on the design details of a unidirectional ring Ti : Al₂O₃ laser, the astigmatism compensation in the Ti : Al₂O₃ laser cavity, and the cavity mode analysis to obtain the optimum pumping geometry. And experimental results using a 3 cm long Ti : Al₂O₃ rod pumped with an Ar⁺ laser are given in the following section.

2. Design of a Ti : Al₂O₃ Ring Cavity

This section gives a description of the ring cavity layout and explains how to compensate the astigmatism in the cavity, and gives the analysis of the cavity mode to obtain the optimum pumping geometry. The configuration of the cavity of a unidirectional ring Ti : Al₂O₃ laser designed in this work, as shown in Fig.1, is similar to the standing wave Ti : Al₂O₃ laser cavity reported previously by Yoon et al.¹⁰⁾. The four mirror ring cavity comprise the Ar⁺ laser pumped laser crystal, a three plate Lyot filter, and a retro-mirror for unidirectional operation.

Ti : Al₂O₃ crystal is longitudinally pumped by all lines of an Ar⁺ laser. The Ar⁺ laser beam is reflected twice by Al-coated mirrors and its vertical polarization is rotated horizontally for the parallel incidence to the horizontally mounted laser rod by a $\lambda/2$ plate placed between

Fig.1 Schematic diagram of a unidirectional Ti : Al₂O₃ ring laser.

(M₁, M₂, r = 20 cm ; R = 99.9% from 750 to 850 nm ; R < 10% in blue-green ; M₄, flat ; T = 2.4% at 790 nm ; f = 20 cm)

Al-coated mirrors. The polarization of light transmitted at the Brewster angle face is in the direction of the crystal c-axis and the crystal c-axis is in the horizontal plane relative to the pump beam polarization. Polarization of the light along the c-axis provides the highest absorption in the blue-green, the highest emission in the infrared, and the lowest residual absorption at the laser wavelength³⁾.

A lens with focal length of 20 cm focuses the pump beam into the laser rod. The focusing is optimised to give a good overlap between the pump and cavity modes in the crystal, then it gives a low threshold. It is experimentally observed that approximately 85 percent of the Ar⁺ laser beam is incident on the crystal and 80 percent of that is absorbed in the crystal.

The laser crystal is 3 cm long and the ends are cut at the Brewster angle and it is mounted on a water cooled aluminium block. The titanium concentration of the laser rod is 0.05 percent by weight. The crystal is placed in a symmetrical position between 20 cm radius of curvature dichroic mirrors placed 22 cm apart (M₁ and M₂ in Fig.1). The other two mirrors are flat (M₃ and M₄ in Fig. 1), where M₄ is the output coupler for the laser. The mirrors (M₁, M₂, M₃)

has 90 percent of transmittance in blue-green and over 99.8 percent of reflectance between 700 and 850 nm. But the output coupler (M_4) is designed to have a transmittance of 2.4 percent. According to Alfrey's model of longitudinally pumped cw Ti:Sapphire laser oscillators¹¹⁾, we can obtain the transmittance of the output coupler which gives the maximum output power for the specific cavity configuration. The calculation for our ring cavity gives 4 percent transmittance of the optimum value¹⁰⁾. Details for the output power are explained in section 3.

As shown in Fig.1, a high reflective mirror located at 10 cm apart from the output coupler makes the laser oscillate in unidirection. It reflects (injects) one of the two output beams into the ring cavity again, then we can obtain unidirectional output beams in the other direction. Usually, a optical diode (one Faraday rotator and one polarizer) or an acousto-optic modulator (AOM) within the ring cavity have been used to obtain unidirectional oscillation for more efficient selection^{2,8)}. A three-plate birefringent filter (Lyot filter) is used as a tuning element for coarse wavelength tuning. The ratio of the plate thickness of the Lyot filter is specially designed to have 1:3:11 for optimum transmission¹²⁾.

Astigmatism in the ring Ti:Al₂O₃ laser cavity is typically generated due to the Brewster-angle cut laser crystal and the focusing folded mirrors used away from normal incidence. Adjusting the angles of incidence on the curved mirrors to approximately 9° (for α) and 39° (for β) in Fig.3, we can compensate the astigmatism generated by the 3 cm long Ti:Al₂O₃ crystal. It has been found experimentally and theoretically that this two angles well compensate the astigmatism of our ring cavity. Figure 2 shows the theoretical predictions of the astigmatism compensation angle α and β as a function of rod length. In this calculation we adopted the theoret-

Fig.2 Calculated results of the astigmatism compensation angle α and β versus the rod length according to the radius of curvatures of folded cavity mirrors. (n , refractive index of Ti:Al₂O₃ crystal)

tical relation commonly used in the astigmatism compensation of the ring dye laser⁷⁾. In Fig 2 the experimental point (○) for our ring cavity is shown together with the theoretical curves, which confirms that the astigmatism generated in the cavity is well compensated. In this configuration, however, there is a slight ellipticity in the output beam, which is likely due to incomplete compensation and misalignment.

The basic cavity as shown in Fig.3 is used for the cavity mode analysis of the Ti:Al₂O₃ ring laser. The focusing folded mirrors M_1 and M_2 make the beam waist of the cavity at the center of the laser crystal. In Fig.3, d is the distance between focusing mirrors M_1 and M_2 , x is the connecting distance of M_2 , M_3 , M_4 , and M_1 , and L is the total resonator length. Then the spacing of the longitudinal modes is given by $\Delta\nu = c/L = c/(d+x)$. In our ring cavity L is 200 cm, thus $\Delta\nu$ is about 150 MHz.

For simplicity, we assume that the cavity beams is Gaussian. The ring cavity in Fig.3 has one principle focal regions in the laser crystal, where the beam waist of the cavity mode must be

Fig.3 Basic construction of a cw ring Ti: Al₂O₃ laser cavity for cavity mode analysis.

matched to that of the pump beam. And the cavity is only stable for certain separation of the focussing mirror combinations M₁ and M₂. The stability condition of the ring cavity can be obtained from the well known ray matrix formula¹³⁾, i.e., $r < d < rx / (x - r)$, where we assume that the focusing folded mirrors have the same radius of curvatures r . Introducing the focusing parameter $\delta = d - r$, the above stability condition could be rewritten as following

$$0 < \delta < (L/2 - r) - \sqrt{(L/2 - r)^2 - r^2}. \quad (1)$$

For the case of our ring cavity $L = 200$ cm and $r = 20$ cm, then the stability region can be calculated from Eq. (1) to be $\delta_{\max} = 2.53$ cm, which implies that the distance between the two focusing folded mirrors must be aligned not over ± 1.265 cm apart from the center of the stability region for stable operation.

The general ring cavity having the off-axis property could be replaced by the equivalent cavity to analyze the cavity modes, where lenses of focal length f' replace some of the cavity mirrors with $f' = r/2$. Using $\begin{bmatrix} AB \\ CD \end{bmatrix}$ system matrix, the latter cavity is then reduced to an equivalent empty cavity (i.e., a periodic sequence of identical lenses separated by d')⁷⁾. Standard formulae for the radius and position of the beam waist can then be applied to the empty cavity, namely,

$$(\pi \omega_{\text{rod}}^2 / \lambda)^2 = d' (4f' - d') / 4 \quad (2)$$

where λ is the wavelength of the cavity beam and d' and f' is obtained from the ABCD rules for the system matrix as following

$$f' = \frac{r^2}{4(r-x)}, \quad (3)$$

$$d' = d + \frac{xr}{r-x}. \quad (4)$$

When the principal waist is found the location and the size of the cavity beam anywhere in the cavity can be determined by applying the ABCD rules backwards. Using Eqs. (2), (3), (4), and the expansion laws for the Gaussian beam¹³⁾, we can obtain the analytical expressions for the beam waists in the rod (ω_{rod}), focusing folded mirrors (ω_m), and in the arm of the cavity (ω_R), where the etalons and optical diode could be inserted, respectively¹⁴⁾.

$$(2\pi \omega_{\text{rod}}^2 / \lambda)^2 = \frac{(d-r)(dr+xr-xd)}{(x-r)} \quad (5)$$

$$(2\pi \omega_R^2 / \lambda)^2 = \frac{(x-r)(dr+xr-xd)}{(d-r)} \quad (6)$$

$$(2\pi \omega_m^2 / \lambda)^2 = \frac{r^2(2dx-dr-xr)}{(x-r)(d-r)(dr+xr-xd)} \quad (7)$$

Since the size of the cavity mode at the laser rod has been fixed, the size of the pump beam waist must be determined for the optimum conversion efficiency at the chosen pumping power. Wagstaff et al.⁷⁾ use a matching parameter $\mu = (\omega_{\text{rod}} / \omega_p)^2$ to estimate the mode matching. The pump beam waist is approximately given by $\omega_p \cong f_{\text{pump}} \lambda / \pi \omega_p'$, where ω_p' is the beam waist of the pump beam (0.7 mm in our system). The slope efficiency reaches a maximum value when μ is approximately unity.

Fig.4 Beam waists inside a ring resonator as a function of the focusing parameter δ . (a) $r = 20$ cm, $L = 2$ m, $\lambda = 790$ nm, and $\delta_{max} = 25.3$ mm; (b) $r = 10$ cm, $L = 2$ m, $\lambda = 790$ nm, and $\delta_{max} = 5.5$ mm.

Fig. 4 shows the behaviors of the above three beam waists in the stability region. The result for $r = 20$ cm, $L = 200$ cm, $\lambda = 790$ nm, and pump focusing lens of 20 cm focal length f_{pump} is shown in Fig.4 (a). The stability region spans 2.53 cm and the matching parameter μ can be obtained from Fig.4 (a) to be 0.77. This value is too low for the optimum pumping of unity.

3. Experimental Results and Discussion

The Ti : Al_2O_3 laser output is measured by a power meter (Spectra Physics 404) and monitored by a Si-PIN photo diode (EG&G FND 100). Without the retro-mirror in Fig.1 the Ti : Al_2O_3 laser oscillates simultaneously in the clockwise (CW) and counter-clockwise (CCW) direction relative to the output coupler M_4 . The

Fig.5 Experimental results of the out power of a Ti : Al_2O_3 laser.

(CW, clockwise output ; CCW, counter-clockwise output)

CW output is 1.5 times larger than the CCW one as shown in Fig.5, when the transmission of the output coupler is 2.4 percent. It seems to be that this difference between the CW and CCW output power is mainly due to the difference of the astigmatism compensating angles α and β as mentioned in section 2.

The maximum unidirectional power is 260 mW at 790 nm when it is pumped with 5.6 W from an Ar^+ laser as shown in Fig.5. The threshold pumping power of Ar^+ laser is 4 W for both unidirectional and bidirectional ring Ti : Al_2O_3 laser. The transmission loss of 15 percent is not counted in this calculation. The output power increases linearly with Ar^+ laser pump power, which gives the slope efficiency of 16 percent. This is comparable to that of 17 percent previously obtained for a standing wave cavity with the same output coupler¹⁰⁾. It is found that the beam waist and divergence of the TEM₀₀ output mode are 1.3 mm and 0.5 mrad, respectively, which are measured at the distance of 1 m apart from the output coupler. The performance characteristics of the Ti : Al_2O_3 ring laser is summarized in Table I.

Table I Performance characteristics of an Ar^{+} -laser-pumped unidirectional $\text{Ti} : \text{Al}_2\text{O}_3$ ring laser.

Specifications	$\text{Ti}:\text{Al}_2\text{O}_3$ Ring Laser
Pump Laser	5 W all-line Ar^{+} laser
Laser Rod	$\phi 0.5 \times 3$ cm, 0.05 wt.% Ti^{3+}
Output Power	260 mW at 790 nm
Beam Divergence	0.5 mrad
Beam Diameter	1.3 mm
Free Spectral Range	150 MHz
Output Polarization	Horizontal
Output Beam Mode	TEM_{00}

When we inject the CCW output beam into the ring cavity using the retro-mirror to obtain unidirectional oscillation, only the CW oscillation output is obtained and the resultant output power is the same as the sum of the CW and CCW output power before injection as shown in Fig.5. The unidirectional oscillation is assured by monitoring the weak leakage power of the CCW beam from M_3 in Fig.1. When the CCW beam is injected into the cavity, the weak CCW beam is abruptly decreased to 100 times lower. This fact indicates that only the CW beam is oscillating. This selection ratio of 100 : 1 is 20 times lower than that of the Roy's method using the AOM⁸⁾.

The method using an external retro-mirror to obtain the unidirectional oscillation in the ring $\text{Ti} : \text{Al}_2\text{O}_3$ laser has lower selection ratio compared to the two methods mentioned in section 2, but it requires a simple optical components. The injection of the CCW beam into the cavity with the retro-mirror may result in increasing power instability as the same manner investigated in the ring dye laser¹⁵⁾. The output power of the ring $\text{Ti} : \text{Al}_2\text{O}_3$ laser is monitored to understand the feature of the power instability by a chart recorder as shown in Fig.6. The time variation of the output power of the unidirectional $\text{Ti} : \text{Al}_2\text{O}_3$ laser is 1.5 times larger in long term stability and 2.5 times larger in short term stability than that of CW output power as shown in Fig.6. The increment of the output power instability can be

Fig.6 Time variation of the output power of a $\text{Ti} : \text{Al}_2\text{O}_3$ laser when a CCW output injection beam is on and off.

understood as the same manner that the injected CCW beam affects the stable oscillation of the counter-propagating CW cavity beam as observed in the other laser systems such as a ring dye laser¹⁵⁾.

We have investigated the free-running wavelength of the $\text{Ti} : \text{Al}_2\text{O}_3$ laser using a 1 m of focal length monochromator (Jobin Yvon 1000) without the Lyot filter. The output beam of the $\text{Ti} : \text{Al}_2\text{O}_3$ laser was entered to the monochromator by a single mode optical fiber. The free-running $\text{Ti} : \text{Al}_2\text{O}_3$ ring laser oscillates at 790 nm and its linewidth is 0.7 nm. This oscillation wavelength is nearly in the center of the gain peak wavelength of the $\text{Ti} : \text{Al}_2\text{O}_3$ laser¹⁾.

As mentioned in section 2, the matching parameter μ of Fig.4 (a) is too low for the optimum pumping of unity. So we are now design some different pair of focusing folded mirrors of 10 cm of radius of curvature and 9 cm of focal length of pump focusing lens and the 0.8 mm of pump beam waist. In this case, as shown in Fig.4 (b), the stability region reduced to 5.5 mm and the matching parameter μ ($= 1.1$) approaches the optimum value of unity. This makes the laser system more sensitive to the mechanical perturbations, but we expect that it gives more laser output power than the former.

5. Conclusion

We have developed a unidirectional $\text{Ti} : \text{Al}_2\text{O}_3$

ring laser, which produces 260 mW output power at 790 nm pumped with 5.6 W all lines of an Ar^+ laser. The slope efficiency of the ring laser is 16 percent. The astigmatism generated in the ring cavity by the 3 cm long laser crystal has been compensated by adjusting the incident angles on the two curved focusing mirrors of the cavity beam to approximately 9° and 39° , and it has been confirmed by the theoretical prediction. The optimum pumping geometry with the matching parameter μ of 1.1 of the $\text{Ti}:\text{Al}_2\text{O}_3$ ring laser is obtained by analyzing the cavity modes.

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