A Study of frequency tunable Ti:sapphire laser for UV lidar

Yong Woo Yi

Provincial College of Damyang

UV 라이다용 주파수 가변 Ti:sapphire 레이저에 관한 연구

이용우

전남도립 담양대학

E-mail : [illegible]@damyang ac kr

ABSTRACT

Multipass Ti:sapphire amplifier for the light source of lidar was developed in an angular-multiplexing, and the characteristics of output energy and spectrum was investigated. In the two-stage multipass amplifier, we obtained the maximum output energy of 42 mJ, the amplification gain of 21 dB and the output efficiency of 26 % on the wavelength of 790 nm. In the tuning range of 715~930 nm the spectral linewidth is 0.05 cm^{-1}. The conversion efficiencies of 35% for SHG at 780 nm and 13% for THG at 390 nm are obtained respectively. The continuous tunabilities of 240~306 nm in UV region and 360~460 nm in deep-blue region could be achieved.

요 약

라이다 광원용 다중통과 Ti:sapphire 증폭기를 각도다중 방식으로 설계하여 출력에너지 및 스펙트럼 특성을 개선하였다. 2-단의 다중통과 증폭기에서 파장이 790nm 일 때, 42mJ의 출력에너지와 21dB의 증폭이득 및 26%의 출력효율을 얻었으며, 715~930nm의 파장가변 영역에서 스펙트럼 선폭은 0.05cm^{-1} 이하였다. 780nm의 파장에서 35%의 SHG 변환효율과 390nm의 파장에서 13%의 THG 변환효율을 각각 얻었다. 결과적으로 240~306nm의 자외영역과 360~460nm의 deep-blue 영역에서 연속적으로 파장을 가변시킬 수 있었다.

Key Words

Lidar, Ti:sapphire, amplifier, linewidth, SHG, THG, tunabilities

I. Introduction

The DIAL(Differential Absorption Lidar) system for air pollutant monitoring requires some tens of energy, hundreds of variable region of wavelength, and narrow spectral linewidth below 0.1 cm^{-1}[1]. For this kind of lidar, there have been dye lasers[2], gas Raman lasers[3], and frequency doubling of solid state lasers which have good tunability. Lately, however, the application of tunable crystal with excellent wavelength characteristics is very activated. Especially, it is very attractive that Ti:sapphire crystal has broadband for oscillation from 660 to 1100 nm and large cross section of stimulated emission about 3x10^{-19} cm^2[4].

In the case of using a Ti:sapphire laser, the single-pass multi-stage amplifier[5], regenerative amplifier[6] and multipass amplifier[7] would be available as an amplification system. The single-pass multistage amplification system has some problems of the low extraction efficiency and the synchronization of pumping. As for regenerative amplifier, it has the merit of the gain increasing by the time-multiplexing, but pockels cell and polarizer between the amplifier and resonator limit the region of tunability. Although multipass amplifier has the merit of broad tunable region and high gains of each amplifier stages, this method has difficulties of optical combination and adjustment of optical pass due to the angular-multiplexing. As mentioned above, various combination of optical devices has been suggested.

In this study, the multipass Ti:sapphire amplifier which pumped on both sides and constructed with some pairs of rectangular prisms has been developed. For the design of optimal multipass amplifier, we have enhanced the amplification gain and saturation characteristics, and we decided the optimal number of pass. The developed two-stage multipass amplifier is able to produce the spectrum narrower than 0.05 cm^{-1}, and UV and deep-blue region of wavelength can be achieved by the second harmonic generation(SHG) and third harmonic generation(THG), respectively.

II. Ewperimental Setup

1. Pumping Laser and Oscillators

To be shown as Fig. 1, the experimental diagram for this study consists of Nd:YAG pumping source, two-stage multipass amplifier, and measuring devices. Pumping source of Ti:sapphire laser is Q-switched Nd:YAG laser of contimumn; sulite-II. Its output characteristics are 6 ns(FWHM) of pulse width, 600 mJ of maximum output energy, and 7 mm of beam diameter. The KTP crystal which has 7x7x7 mm^3 of volume is for SHG with the output of Nd:YAG laser. The maximum output energy of SHG was 160 mJ. 1.06 µm and 532 nm wavelength is separated by dichroic mirror, the 532 nm wavelength propagates through P-polarizer and 532 nm bandpass filter, and it is divided by two beam splitters to pump the first and second amplifiers. Another separated 532 nm wavelength is divided by beam splitter with 50 % reflectivity and passed through the rectangular prism to pump the Ti:sapphire crystal both ends. For the pumping of Ti:sapphire oscillator, we selected the focusing lens(f.l.=0.5 m), and also we used another focusing lens(f.l.=1 m) for two-sage amplifier.

Multiple-prism Littrow grating(MPL) type Ti:sapphire oscillator[8] consists of the multiple-prism beam expander, the diffraction grating of 1800 g/mm, and the output mirror of 15 % transparency. The total length of the resonator is 45 cm. As the output characteristics of Ti:sapphire oscillator, the continuous tunability from 715 to 930 nm was enabled. At 790 nm wavelength, the output energy of 300 µJ with 0.05 cm^{1} spectral linewidth is obtained. At this condition, the beam diameter was o.6 mm and its beam divergence was 1.2 mrad.

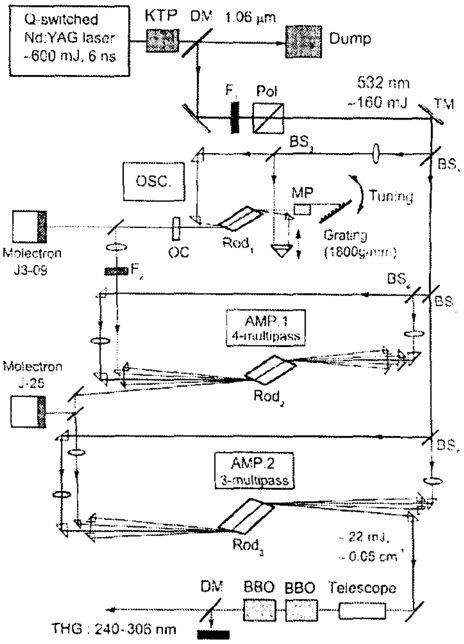

Fig. 1 Schematic diagram of the two-stage Ti:sapphire laser based UV and deep-blue laser continuously tunable from 240~306 nm.

To measure the energy in our experiment, we used the energy meters of J3-09 and J-25 made by Molectron Co.. To analyze the size of laser beam, laser beam analyzer(1ba-100A, Spricon) was adopted. By the way, we were able to read each wavelength with 1-meter monochrometer (Acton co., AM 510). The Fabry-Perot etalons which have 4 and 2 mm thickness, produced the ring patterns for the measurement of the spectral linewidth. Also their intensities were to measure by 1024 pixel CCD camera and 286 IBM-PC.

2. Ti:sapphire Multipass Amplifier

As shown in Amp. 1 and Amp. 2 of Fig. 1, the multipass amplifier includes the amplification crystal and rectangular prism pair. We collimated the signal beam to the amplification crystal by inserting the focusing lens(f.l.=1.2m). At the amplifier, the multipass structure means that the amplification crystal is cut with Brewster angle. Therefore, it would be constructed with the horizontal-angular structure at Fig. 1. To solve the optical problem that we have to pass the ray through the amplification crystal some times, the round-trip of the incident beam was done by 15x15x15 mm3 rectangular prism pair. The limitations of the pumping beam path and the superposition of signal cause the limited passing numbers not much more than ten passes of input signal to amplification crystal. The sizes of pump beam and the input beam of amplifier, as well as the image size reflected on the face of the amplification crystal, were measured and set by laser beam analyzer. The size of first amplifying crystal is 8 mm(Φ)x20 mm(L), cutting both sided with 60o24'5" as Brewster angle, and its absorption is 97% for the second harmonic generation of Nd:YAG laser.

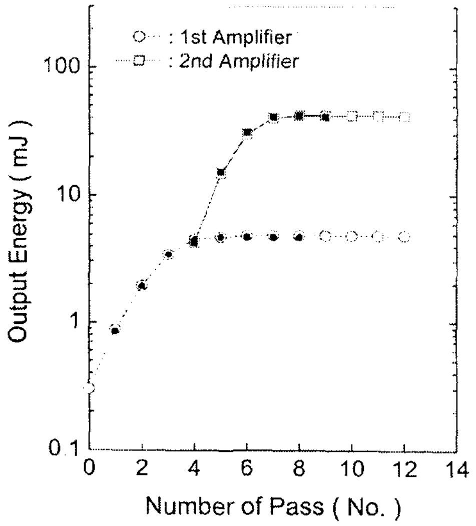

Fig. 2 Comaprison of both amplifiers' performances with a saturation model at 790 nm.

At the second amplifier, the signal beam amplified by first amplifier is collimated as the diameter of 1.6 mm, using the focusing lens(f.l.=1 m). Its beam size can be controlled like pump beam. The concentration of the amplification crystal is 0.07 % and the size is 8 mm(Φ)x15 mm(L). It also has Brewster angle at both sided and the absorption is 97% for the second harmonic generation of Nd:YAG laser.

3. SHG and THG

There are a variety of nonlinear crystals that can be phase-matched for SHG of at least some fraction of the Ti:sapphire tuning range. For SHG experiments over the entire Ti:sappire tuning range, we have compared phase-matching angles of KH_2PO_4(KDP), β-Ba_2BO_4(BBO) and LiB_3O_5(LBO) for both type I and type II configurations. As a result, the available physical size of BBO material and the relatively small change in phase-matching angle with wavelength allows one crystal to be used over the entire Ti:sapphire tuning range. We have used a BBO crystal of 5x5x7 mm3 (type-I, θ=28°, Φ =90°).

With the type II THG configuration, the angle tuning over about 30° is required to cover the 700~940 nm fundamental tuning range. A type II THG crystal following a type I SHG crystal is advantageous, because the orthogonal polarization states mixing process in the THG crystal. A telescope is used for adjusting the incident power density to the crystal and also a dichroic mirror is used for dividing UV and deep-blue wavelengths.

III. Experimental Results

1. Amplifier Performance

Fig. 2 shows the comparison of both amplifiers' performances with a saturation model. The open symbols show the calculated output for each pass, and the filled-symbols are experimental points. The pump energy incident to the first amplifier is 34mJ, both sided energy density is 2.1J/cm^2. The profile of pump beam is Gaussian distribution, the diameters of input signal and pump beam are 1.1mm and 1.0mm at point of incident surface on amplification crystal, respectively. When the signal beam propagated the multipasses through amplification rod, its covering cross section of pump beam, the energy loss is minimized. We have obtained the output results on changing the number of pass eight times and determined the optimal number of pass comparing well with the analysis of saturation model of the first amplifier[9]. The loss of number of pass is analyzed by gain and saturation equations on multipass amplifier[10]. Assuming that monochromatic laser input signal E_i is propagated through amplification crystal on one pass, we get the output fluence E_{out1} represented as follows[11].

$$E_{out1} = E_{st}\ln[1+\left\{\exp(\frac{E_i}{E_{sat}})-1\right\}\exp(\beta E_{st}L)] \quad (1)$$

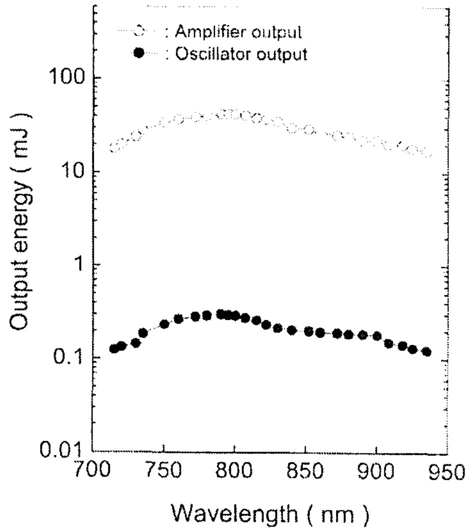

Fig. 3 Tuning curve of multipass Ti:sapphire amplifier and oscillator.

Here, E_{sat} is the saturation fluence, $g_0$is the small signal gain coefficient and E_{st} is the stored energy. For the comparison of experiments with calculations, this model has been applied for each amplifier as shown in Fig. 2. When the input pulse of energy of 300 μJ and spectral linewidth below 0.1 cm^{-1} from Ti:sapphire master oscillator is injected in amplifier, the saturation condition is determined. The output energies of four and five passes are 4.7 mJ and 4.9 mJ, respectively, and is no more increased over five passes.

Increasing the number of passes to six or seven, the output is decreased and laser beam quality is worse. In the first amplifier, four passes is determined by saturation of energy as optimal condition, it is obtained increase of the output energy in the second amplifier.

The second multipass amplifier is both sided pumped, total pump energy is 110 mJ, energy density is 3.1 J/cm2 on each surface of rod. The pump energy density of amplifier is limited below 4 J/cm2 because the high power density up to 3 times of the average in peak point of pulse gives the considerable damage to rod. Incident signal to the second amplifier has the energy of 4.5 mJ, the output energy of 4.8 mJ from first amplifier is reduced to energy of 4.5 mJ because of optical loss. The diameter of signal beam and pump beam on surface of rod are 1.6 mm and 1.5 mm, signal beam is rounded five times by using the prism pairs. In this experiment, the more the energy densities of pump beam and input signal increase, the more the number of passes of saturation point decrease. The extraction efficiencies are 25 % for the first four-pass amplifier and 44 % for the second three-pass amplifier, and total output efficiency is 26 % for entire Ti:sapphire system.

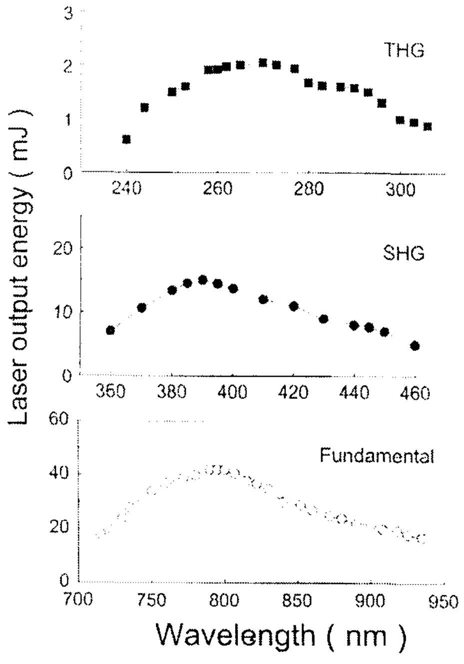

Fig. 4 Actual output energy at a 10 hz repetition rate. THG, SHG and fundamental outputs are shown.

2. Tunability

Fig. 3 shows tuning curves of two-stage multipass amplifier and oscillator. Tuning curve of amplifier is coincided with the tunability of 715~930 nm obtained from oscillator, the peak value of output energy is obtained at 800 nm wavelength. When we have compared the amplification gains in center and edge regions in this tuning curve, the amplification gains are 21 dB at center wavelength of 790 nm, 18 dB at 705 nm and 19 dB at 840 nm.

3. Second and Third Harmonic Generation

Fig. 4 shows tuning data with the fundamental, second harmonic and third harmonic pulse energies, That is, the sharp drop of the THG energy at the endpoints is directly related to the lower energy provided in these regions. Here, the maximum peak power is below 30 MW in the average intensity terms used by Eimerl[12] for the power threshold definition. We observed 35 % conversion efficiency of SHG at 780 nm fundamental wavelength and the tuning range of 360~460 nm. The conversion efficiency of THG is 13 % at 390 nm wavelength and tuning range is 240~306 nm. We should point out that the spectral linewidth is confirmed to be ~ 0.05 cm^{-1} above entire wavelength region.

IV. Conclusions

For the application of DIAL measurement in UV and blue region wavelength, we have developed small-size Ti:sapphire amplifier system with a high efficiency and narrow spectral linewidth below 0.05 cm^{-1} and obtained UV and deep-blue region wavelengths in the second and third harmonic generation of tunable near infrared wavelength. A Ti:sapphire oscillator consists of grazing-incidence grating with 1800 g/mm diffraction grating and a output coupler with reflectance of 85 % at 800 nm. The tuning range is from 715 to 930 nm and spectral linewidth is 0.05 cm^{-1}. The output energy of oscillator is 300 μJ, the output beam after passing two-stage amplifiers has the energy of 42 mJ and the total efficiency for pumping is 26 %. For the SHG in infrared wavelengths, one beta barium borate(BBO) nonlinear crystals is used and their sizes are 5x5x7 mm^3 (type-I, $\theta=28°$, $\phi=90°$). For the THG, two beta barium borate(BBO) nonlinear crystals is used type-II. A telescope is used for adjusting the power density incident to the crystal and a dichroic mirror is used for dividing UV and deep-blue wavelengths. We have obtained the conversion efficiency of 35% for SHG at 780nm and 13% for THG at 390 nm, respectively. Continuous tunabilities of 240~306 in UV region and 360~460 nm in deep-blue region could be achieved. Most importantly, we should point out that the spectral linewidth is confirmed to be ~0.05 cm^{-1} above entire wavelength region.

As a results, we have built a two-stage multipass Ti:sapphire amplifier able to amplify the narrowed pulses below 0.05 cm^{-1} and generate UV and deep-Blue region. This system presents strong advantages in terms of excellent beam quality and good potential for wavelength tuning. This system has expected to apply for the measurements of water vapor with absorption spectrum of 717~738 nm and air pollutants with UV and beep-blue region in atmospheric[13,14].

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