Efficient blue light generation by cascade, intra-cavity second harmonic and sum-frequency generation of a Nd:YVO₄ laser

P K Datta, S Mukhopadhyay, S K Das and G K Samanta
Department of Physics & Meteorology
Indian Institute of Technology, Kharagpur-721302, INDIA
E-mail: pkdatta@phy.iitkgp.ernet.in

ABSTRACT

Ultraviolet radiation at third harmonic of Nd:YVO₄ is generated by intracavity second harmonic and sum-frequency generation in two successive LiB₃O₄ crystals. The different temporal regimes of operation (e.g. cw, Q-switched and mode-locked) of the laser and corresponding intracavity third harmonic generation are demonstrated. The mode-locking is realized by nonlinear mirror based on intracavity second harmonic generation and the third harmonic generation contributes to the improvement of the stability by inverse saturation effect.

Keywords: Q-switching, Mode-locking, Nonlinear mirror, Inverse saturation

1. INTRODUCTION

The short wavelength of UV radiation has found tremendous attention for its wide application in, such as, spectroscopy, optical data storage, laser printing, undersea communication, medical treatment, micromachining, microdrilling, sputtering thin films, surface cleaning and stripping of plastics, ceramics and metals. Intracavity third harmonic generation of the Nd lasers have the promise for realization of compact and efficient UV source. Generation of continuous wave (CW) UV radiation form such source is quite simple but the same resonator cavity can be used to generate ultrashort pulses provided proper mode-locking (ML) technique is employed. Here we report an all-solid-state compact UV source by subsequent intra-cavity second harmonic generation (SHG) and sum frequency mixing (SFM) in a Nd:YVO₄ oscillator in cw, Q-switched and mode-locked regime. The laser is operated in actively Q-switched mode to obtain nanosecond pulse by inserting an acousto-optic Q-switch in the laser cavity. Whereas, nonlinear mirror (NLM) technique¹-⁴ is used to realize passive mode-locking for the generation of picosecond pulses. In NLM systems, a frequency doubling nonlinear crystal (NLC) is incorporated in the laser cavity and placed near a dichroic mirror used in place of the usual output coupler. The dichroic mirror partially reflects the fundamental wave (FW) but totally reflects the second harmonic (SH) beams. The FW generates SH in its first pass and if the SH beam experiences a proper phase shift with respect to the FW beam, the SH power is almost totally reconverted into FW during the second pass through the NLC. As the second harmonic generation (SHG) is a second order nonlinear optical process, the NLC along with the dichroic mirror behaves as an NLM having an intensity-dependent reflection coefficient. Under this condition the laser losses decrease with an increase in the peak power of the FW beam and so the behavior is the one of a fast saturable absorber. The nonlinear mirror initiates the generation of ultrashort pulse. The advantage of this mode-locking over semiconductor saturable absorber is its simplicity in design and can be operated in wide spectral range. However, the minimum critical intra-cavity pulse energy ($E_C$), defined as $E_C = 2\sqrt{\Delta P \tau E_L}$, required for stable cw ML⁵,⁶ is too high to realize with SHG-NLM without optical damage of intra-cavity components. Here $P_s$ and $\Delta R$ are the saturation power and the depth of modulation of NLM absorber, $E_L$ is the saturation energy for the laser crystal, and $\tau$ is the pulse width. As such SHG-NLM only, can not prevent passive Q-switching tendency. The third harmonic generation (THG) by SFM process can be utilized both for generating UV pulses as well as stabilizing the nonlinear mirror cw mode-locking. The UV generation by SFM effectively reduces the critical intra-cavity pulse energy for stable cw mode-locking because of the inverse saturation effect.⁶
2. EXPERIMENT

2.1 Laser layout

The schematic of the oscillator cavity is shown in Fig. 1. The active material is a 4X4X8mm³, a-cut, Nd:YVO₄ crystal having Nd³⁺ concentration of 0.5% and antireflection coated on both faces for wavelengths 1064nm and 808nm. To reduce the effect of undesired reflection the crystal is tilted by angle of 2°, and is placed in an air cooled heat exchanger. The crystal is end pumped by a fiber coupled laser diode array, emitting radiation of wavelength 808nm and maximum output power of 15W, through the rear mirror (RM), which is anti reflection coated at 808nm at the rear side and has high reflectivity (>99.5%) for 1064nm on the other side. The pump beam coming out from the fiber of core diameter 0.6mm and numerical aperture 0.22 is imaged on the Nd: YVO₄ crystal using two lenses of focal length 15mm and 12mm to a spot size 0.48mm. A 15-mm long LiB₃O₅ crystal (LBO1), cut for type I phase-matching for the SHG of 1064 nm, is followed by another 12mm long LiB₃O₅ crystal (LBO2) cut for type-II SFM of 1064 nm and 532 nm and are placed very close to the output coupler. Two concave mirrors M₁ and M₂ of radius of curvature 500mm and 250mm respectively are used to focus the beam between the two LBO crystals. An Acousto-optic Q-switch (AOQS) with faces cut for Brewster angle at 1064 nm, is inserted in the cavity. The AOQS is driven by a radio frequency signal of 27.2 MHz with a modulation available in the frequency range 0-50 kHz.

2.1 CW free running laser

The Z-shaped laser cavity was first optimised with the arm lengths of 250 mm, 405 mm and 230 mm for TEM₀₀ mode with maximum output power at 1064nm then the two LBO crystals were adjusted for maximum 355nm generation. We used a output coupler, which is a dichroic mirror with reflectivity of 99.5% at 532 nm and 81% at 1064 nm and 54% at 355nm radiation. The generated UV radiation is separated from other wavelengths by a dispersive prism. The generated radiation is confirmed to be of wavelength 355nm by a monochromator. For 10W of laser pump power (at 808nm) cw power of 0.5 mW is measured at 355 nm. The optics used for the cavity is not appropriate for efficient generation of 355nm. However, optimized cavity optics can provide a better efficiency to the 355 nm output power.
2.2 Q-switched laser

The laser was operated in actively Q-switched mode by turning on the acousto-optic Q-switch and the generated UV power is measured to be 10 mW corresponding to pulse repetition rate of 25 kHz. The optics used for the cavity is not appropriate for efficient generation of 355 nm. If optimised optics were used the power would have been 25 mW and the corresponding peak power is 7.0 W. Under Q-switched operation the pulse width is observed to vary over the range 126 ns to 301 ns corresponding to the pulse repetition rate (determined by the modulation frequency) form 10 kHz to 50 kHz. The stable Q-switched operation was found to occur in the modulation frequency range of 20 kHz – 45 kHz. The maximum pulse energy under stable Q-switched operation is measured to be 1.0 µJ corresponding to pulse repetition rate of 25 kHz and laser pump power of 10 W.

2.2 CW mode-locked operation

For CW mode-locked regime of operation we used an output coupler which is a dichroic mirror with reflectivity of 99.5% at 532 nm and 78% at 1064 nm and 82% at 355 nm radiation and the Q-switch is turned off. The nonlinear mirror comprising of SHG crystal and the dichroic OC are capable of mode-locking the laser but the mode-locking stability is always poor because of the interference of the passive Q-switching instability. The higher upper state life time of the solid state gain medium along with the high saturation power and depth of nonlinear loss modulation of the nonlinear mirror saturable absorber facilitate the passive Q-switching interference and the laser sets in simultaneous Q-switched and mode-locked (QML) operation. The intracavity THG provide the effect of inverse saturation of the nonlinear loss which reduces the depth of nonlinear loss modulation as well as the saturation power.

![Oscilloscope trace of the mode-locked pulse train](image)

Figure 2: Oscilloscope trace of the mode-locked pulse train

\[ E_C = \sqrt{2\Delta R P_\Delta \tau / \left( \tilde{\beta}_{\text{THG}} + (1/2)E_\Delta \right)} \], where \( \tilde{\beta}_{\text{THG}} = \beta/3A_{\text{eff}} \tau \) is the inverse saturable absorber coefficient related to THG. Here, \( l \) is the THG crystal length and \( A_{\text{eff}} \) is the effective beam area in the crystal. The parameter \( \beta = 8\pi^2 d_{\text{eff}}^2 1/e_0 n_1 n_2 n_3 c \lambda_1^2 \), where \( d_{\text{eff}} \) is the effective nonlinear coefficient for SFG, \( n_1, n_2, n_3 \) are the refractive indices of LBO at FW, SH and TH radiation. The laser generates stable cw mode-locked pulses of repetition rate 170 MHz and of width 29 ps. The oscilloscope trace of the output pulse train is shown in Fig. 2. The pulse width was measured for the wavelength 1064 nm by the noncollinear second order intensity autocorrelation employing a 3 mm long BBO crystal. The autocorrelation trace is shown in the Fig. 3. The mode-locking is found to be self starting as well as self sustained for the pump power over 10.7 W corresponding to the average output power of 3.25 W at 1064 nm. Mode-locking is found to exist even for the pump power as low as 10 W, however it was not self sustained. For lower optical damage threshold of the cavity mirrors we restricted the pump power up to 12.1 W corresponding to average mode-locked output power of 4.53 W at the 1064 nm. The ML is...
robust, stable and is never affected by passive Q-switching instability and the beam quality is measured to be nearly TEM$_{00}$.

Inverse saturation stabilizes the cw mode-locking but tend to increase the pulse width far beyond the gain-bandwidth limited value. The laser im general can generate mode-locked pulses at wavelength 1064nm and 355nm, however for only 1064 nm output the pulsewidth can be reduced significantly. The inverse saturation that is achieved for the

![Figure 3: SHG intensity autocorrelation trace. Dots: experimental data; Continuous line: Gaussian fit](image)

perfect phase matching of the THG process is much higher than the minimum value required to reduce the minimum critical pulse energy below the available intracavity pulse energy. The THG crystal can properly be detuned from the exact phase matching to reduce the TH loss but it introduces self phase modulation (SPM) which plays a significant role to shorten the pulse effectively. Group velocity dispersion in the two nonlinear crystals can also broaden the pulse. Although the calculated group velocity delay for interacting wavelengths in the two LBO crystals is only $\approx 8$ ps, it has significant effect on the steady state pulse width. Proper intra-cavity group velocity dispersion (GVD) compensation can give a significant reduction in the pulse width.

REFERENCES