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CHARACTERIZATION OF A PULSE WIDTH TUNABLE PICOSECOND Nd:YAG LASER

S. K. Sudheer, S. Vijay Shukla[a], S. M. Oak[a], R. Arya[b], V. P. N. Nampoori[c]

Department of Optoelectronics, University of Kerala, Kariavattom- 695581, Trivandrum, Kerala, India
[a]Ultrafast Studies Section, Laser Physics Division, Centre for Advanced Technology, Indore-452013, India
[b]Production Unit, Centre for Advanced Technology, Indore-452013, India
[c]International School of Photonics, Cochin University of Science and Technology, Kochi, India

A hemispherical Nd:YAG Laser resonator was characterized with passive mode-locking applied and by using a contacted variable path length saturable absorber dye cell. A compact power supply was designed using resonant conversion topology and was fabricated. The efficiency of power supply achieved at full load was 95%. At full load, the turn on of switches is achieved at nearly zero voltage and current. The efficiency at 75 mA was 70%. The reduction achieved in volume and weight as compared to the conventional scheme, is about 4 and 5 times respectively. The output energy optimization of laser was achieved in the free running mode and mode-locked forms. The time delay between the triggering of flash lamp and the emission of the laser pulses was investigated for different operating voltages. It is found that the time delay between the triggering of flash lamp pulse and emission of laser pulses is decreasing as operating voltage increases. The jitter in the time delay is measured for five consecutive shots and is found to be ± 2 μs. The path length of the dye cell used for passive mode- locking was varied and corresponding variation in output pulse width was noted for different operating voltages. The triangular configuration of TPF was used to measure the pulse width of the laser output. It is found that the width of individual pulses in the mode locked train is directly proportional to the optical path length of the dye cell. A gradual reduction in pulse width with increase in operating voltage was also noted.

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1. Introduction

Optoelectronics has acquired a new momentum due to the developments in the areas of solid state lasers and nonlinear optical materials. Such lasers can be mode-locked and characterized using the nonlinear properties of saturable absorber dyes to attain high power and capability of pulsed operation [1,2]. Laser power supplies can be made compact using highly efficient new techniques like switch mode resonant conversion along with pulse width modulation (PWM) control. These lasers are useful in the studies of ultra fast phenomena and optical nonlinearities of various materials. Picosecond optical pulses provide a unique means for studying processes associated with the interaction of light with matter [3]. Such high intense optical pulses can be applied for optical parametric oscillation, degenerate four wave mixing (DFWM) and optical limiting experiments. Implementation of these nonlinear and ultrafast studies has required the development of new measurement techniques capable of picosecond time resolution [4-7]. Thus it is now possible to investigate on a picosecond time scale the interactions of light pulses with molecules, including the direct measurement of both intra-molecular and intermolecular relaxation times [6-8]. Direct measurement of picosecond pulse width by the combined use of photo-detectors and oscilloscopes is no longer adequate to temporally resolve the pulse being produced. For CW lasers SHG method for measuring pulse width is good. But for pulsed lasers it cannot give good results, since a shot to shot jitter in the energy of the pulse and its duration will be occured.

Two Photon Fluorescence (TPF) method is a suitable method for the measurement of pulse width of pulsed lasers [5-10]. It is single shot method. TPF displays were first observed by Giordmaine *et al.* [11] using a second harmonic pulse train derived from a mode-locked Nd:Glass laser. Pulse overlap was achieved by the normal reflection of the second harmonic pulses at a mirror surface immersed in the TPF dye. Rentzepis and Duguay overlapped a train of intense pulses at 1064 nm with a train of weak second harmonic pulses at 532 nm [12]. The triangular configuration was developed in later experiments by De Maria *et al.* [13,14].

2. Experimental

In the present work an Nd:YAG laser was characterized using a hemispherical resonator and passive mode-locking applied. A compact simmer current source was designed using resonant conversion and was fabricated. The output optimization was achieved in the free running mode and mode-locked forms. The time delay between the triggering of flash lamp and the emission of the laser pulses was investigated for different operating voltages. The above time delay is associated with a jitter and was noted. The path length of the dye cell used for mode-locking was varied and corresponding variation in output pulse width was noted. The variation in pulse width with operating voltage was also noted. The contacted dye cell acts as a tunable passive mode-locker with a minimum path length of 0.38 mm and a maximum of 1.27 mm. The regenerative Nd:YAG laser oscillator is essentially a combination of optical amplifier and resonator, the output of which was mode-locked using the nonlinear optical saturable dye [15-17]. The triangular configuration of TPF was used to measure the pulse width of the laser output.

2.1 Power supply

A xenon flash lamp was used to pump the Nd:YAG laser rod of size (ϕ 3) $\times$ 75 mm. The lamp was energized using a power supply consisting of three sections. An ignition section which uses SCR as the switching element and the output ratings are 20 kV with 5 μs. Once the discharge is initiated within the flash lamp, it can be maintained using the simmer current source delivering an output of 1 kV with a current range of 50 - 150 mA. There are many advantages in using a simmer current source [18-20]. The above two units were used with the charging unit which delivers 40 J of energy per pulse to the flash lamp at the rate of 10 pulses per second. We have developed a series resonant converter (SRC) with pulse width modulation (PWM) control scheme for the simmer current source. The inverter in the simmer current source operates at 40 kHz and uses IRF840 MOSFETs and its body diode as transistor switches, and antiparallel diodes. The power supply has been tested on resistive load of 8 kohm at 200 W and different flash lamps with 8 kohm ballast for full range of load current variation. The efficiency achieved at full load was 95%. At full load, the turn on of switches is achieved at nearly zero voltage and current. The efficiency at 75 mA was 70%. The reduction achieved in volume and weight with the present scheme, as compared to the conventional scheme, is about 4 and 5 times respectively.

2.2 Output energy optimization and free running mode of operation

A single elliptical pump cavity was used for the efficient coupling between a pump source and laser material. A hemispherical resonator consisting of a concave mirror (R_1 = 100%) and a plane mirror (R_2 = 70%) separated by a distance of 1.42 m provides the function of a highly selective feedback element by coupling back in phase a portion of the signal emerging from amplifying medium. The resonator was designed based on the equations derived by Kogelnik *et al.* [21] and also by H. Kogelnik [22] to provide the beam sizes w_1 and w_2 at the mirrors as given below.

$$w_1^2 = w_0^2 = (\lambda / \pi) \sqrt{[L(R_2 - L)]} \quad (1)$$

$$w_2^2 = (\lambda / \pi) \ R_2 \sqrt{L/(R_2 - L)} \quad (2)$$

where w_0 is the size of the beam waist, R_1 and R_2 are the radii of curvature of the mirrors. The mode parameters obtained with a plane mirror and concave mirror of radius 5 m are:

$$w_1 = w_0 = 0.872 \text{ mm}; \ w_2 = 1.03 \text{ mm}.$$

The resonator was aligned and the power supply was operated at a repetition rate of 10 pps. The laser output was visualized on Tektronix Model TDS 220, Two Channel Digital Real Time Oscilloscope-100 MHz, 1 GS/s using a silicon photo detector. Tilting the front mirror and aperture optimized the output. The angle of tilt of the front mirror in both vertical and horizontal directions was varied and corresponding output energies were noted. The temporal stability of the laser pulses was noted by measuring the jitter in time delay between the triggering of flash lamp pulse and generation of laser pulses. The delay between triggering of the flash lamp and emission of the output laser pulses was noted for different operating voltages. The variation of time delay with operating voltage was plotted and is shown in Fig. 1.

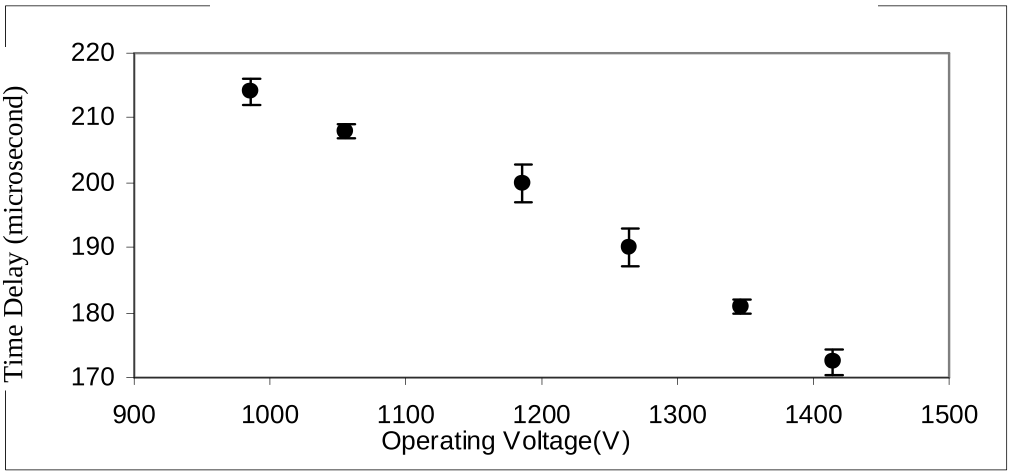

Fig. 1. Variation of time delay with operating voltage.

2.3 Passive mode-locking with variable path length dye cell

The laser was passively mode-locked using nonlinear absorption of saturable absorber as described by H. W. Hocker et al. [23-26]. The intracavity nonlinear absorber used was Eastman #9860 dye. The dye was dissolved in 1, 2 dichloro ethane taken in the variable path length dye cell-model FDC-100, Laser metrics, Inc. To get most reliable performance from mode-locked dye systems, the dye was circulated through the cell from a large reservoir. The pumping action assures uniform mixing of the dye because of the large volume, the concentration of the dye remains constant over a long period of time and fresh dye is exposed to each laser pulse. The dye cell used was as a tunable passive mode-locker which consists of several close fitting precision machined parts. It was used for precise optimization and stability of the mode-locked pulse train.

The minimum adjustable path length is 0.38 mm and the maximum is 1.27 mm. The dye reservoir was filled with 1 litre of 1,2 dichloroethane and a slow flow was allowed so as to avoid turbulence. After the system alignment, the output energy was optimized once again. The laser was operated in the free running mode and 1 mm aperture is adjusted to ensure that TEM_{00} mode alone is oscillating. About 600 ml of the dye solution was filled in the reservoir and the laser was again operated. The concentration of the dye was varied continuously until a good mode-locked train of pulses was obtained.

2.4 Pulse width measurement using TPF method

The output pulse width was measured using TPF method and the schematic diagram of the measurement geometry is illustrated in Fig. 2.

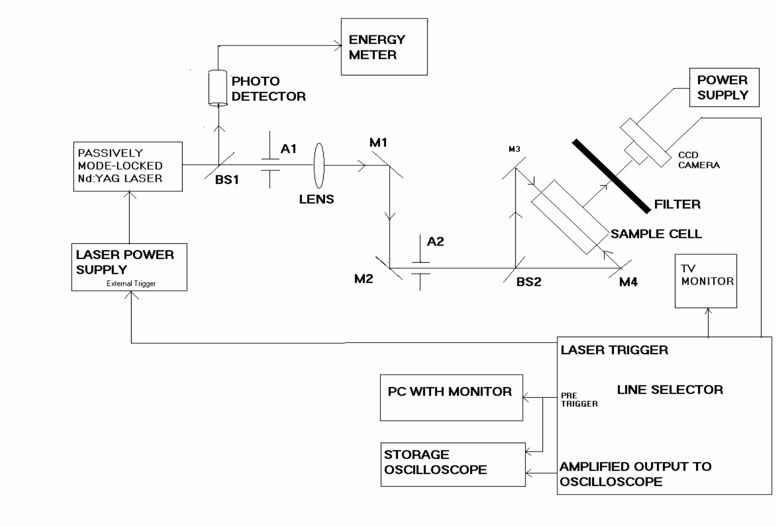

Fig. 2. Two photon fluorescence experimental setup.

The passively mode-locked Nd:YAG laser pulses were passed through the optical system. The magnitude of the electric field vector of the plane wave optical pulse emitting from the laser at a fixed point in space may be expressed as a Fourier integral as given below [27]:

$$E(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e(\omega) \exp(-i\omega t) d\omega \tag{3}$$

Taking inverse Fourier transform of the above expression,

$$e(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} E(t) \exp(i\omega t) dt \tag{4}$$

By omitting the negative frequency components in equation (3) and by including a factor of 2 to ensure that E(t)=Re V(t),

$$V(t) = \frac{1}{\sqrt{2\pi}} \int_{0}^{\infty} 2e(\omega) \exp(-i\omega t) d\omega \tag{5}$$

where *V(t)* is the analytical signal associated with the electric field of the optical wave packet.

A 50% beam splitter divides the pulse under investigation into two equal parts and each replica travels equal distances and overlap in a 5×10^{-3} M solution of Rhodamine 6 G in ethanol exhibiting two-photon absorption and fluorescence. Neutral density filters were used for attenuation of the μs pulses. A time resolved photograph of the fluorescence trace was taken using a CCD camera and output from it was given to various measuring devices such as Cathode Ray Oscilloscope and PC monitor. The time-integrated photograph recorded from the side shows enhanced fluorescence where fluctuations or isolated pulses overlap with each other. The main advantage of the TPF method is that the spatial distribution of the fluorescence intensity is directly related to second order correlation function $G^{(2)}(\tau)$, also called fourth-order coherence function and is defined as follows:

$$G^{(2)}(\tau) = \left\langle V(t)V(t+\tau)V^*(t)V^*(t+\tau)\right\rangle \tag{6}$$

The complete auto correlation profile is displayed simultaneously as a function of distance ($z = 2c\tau$) from the center of the overlap region. The fluorescence signal is directly proportional to the time averaged fourth power of the electric field and can be written as follows:

$$F(\tau) = k\left\{G^{(2)}(0) + 2G^{(2)}(\tau) + R_{TPF}(\tau)\right\} \tag{7}$$

$R_{TPF}(\tau)$ contains rapidly varying terms and the constant k depends on the photochemical properties of the dye and the geometry of the detection equipment. Away from the region of overlap, $F(\tau) = k\,G^{(2)}(0)$ and relative to this minimum background level the fluorescence signal is given below:

$$S_{TPF}(\tau) = \left\{1 + \frac{2G^{(2)}(\tau) + R_{TPF}(\tau)}{G^{(2)}(0)}\right\} \tag{8}$$

Once again the fringes are far too fine to be detected experimentally since they are averaged out by the limited spatial resolution of the recording camera. So the effect of $R_{TPF}(\tau)$ can be neglected. At the region where the overlap is maximum, a bright vertical line will be recorded with a contrast ratio of 3:1. The contrast ratio K is the ratio of amplitude of the peak to that of background. Using an energy meter, the energies at every instant were displayed. The half-width of the fluorescence peak Δz and contrast ratio K are measured. The TPF pulse width t_{TPF} is the ratio of distance to group velocity. So t_{TPF} can be given as follows.

$$t_{TPF} = (\Delta z)n/c \tag{9}$$

where n is the refractive index of the two photon fluorescence dye solution, *ie* ethanol (n = 1.3614) and $c = 3 \times 10^{8}$ m/s, the velocity of light in vacuum. The method will provide a complete measurement of $G^2(\tau)$ with a single pulse. Correlation takes place in the liquid dye solution that has no absorption at the pulse wavelength but fluoresces in the presence of high intensity by virtue of two photon absorption. The TPF intensity profile was monitored in the storage oscilloscope. So t_{TPF} can be calculated from the fluorescence trace recorded in the CRO.

To calculate the actual pulse width t_p the oscilloscope time scale was calibrated. A meter scale was illuminated and the intensity pattern was displayed on the CRO. From the pattern the time corresponding to 1 mm was found out as 1.5 μsec. Therefore 1 sec corresponds to 666.67 meters. Then time t_{TPF} corresponds to 666.67 t_{TPF} meters. So pulse width t_p can be expressed as follows.

$$t_p = \sqrt{2}\ [\,666.67t_{TPF}]n/c \text{ seconds} \tag{10}$$

The pulse width is multiplied by a factor $\sqrt{2}$ assuming that the pulse shape is Gaussian. Thus the pulse width t_p can be calculated directly from the half width of fluorescence trace. The measurement was repeated for values of the passive mode-locker dye cell thickness equal to 0.38 mm and 1.27 mm. For various operating voltages the output pulse width was measured. To demonstrate the variation of t_p in one of the best experimental runs the calculated values of t_p (Gaussian pulse shape) for a series of four consecutive measurements for each dye cell thickness are noted. The operating voltage of the laser power supply and corresponding contrast ratios are also noted.

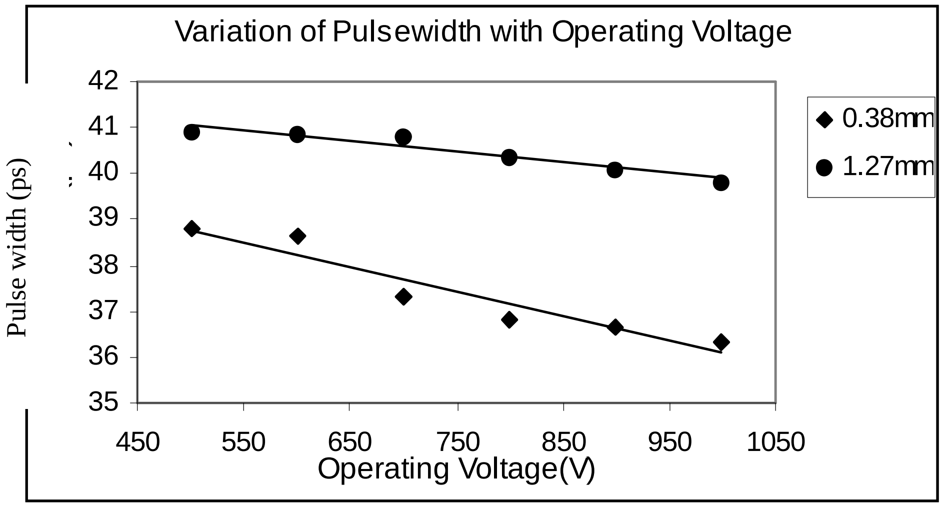

Fig. 3. Variation in output pulse width with operating Voltage and width of Dye cell.

3. Results

The efficiency of the simmer current source achieved at full load was 95%. At full load, the turn on of switches is achieved at nearly zero voltage and current. The efficiency at 75 mA was found to be 70%. The reduction achieved in volume and weight with the present scheme, as compared to the conventional scheme, is about 4 and 5 times respectively. It is found that the time delay between the triggering of flash lamp pulse and emission of laser pulses is decreasing as operating voltage increases. As operating voltage increases, the rise time of the flash lamp pulse decreases in a trivial manner. The jitter in the time delay is measured for five consecutive shots and is found to be $\pm$ 2 μs.

The average pulse duration t_p values are calculated as 36.9 ps and 40.46 ps respectively for minimum and maximum path lengths of the dye cell with average contrast ratios 2.755 and 2.9. It is found that the width of individual pulses in the mode locked train is directly proportional to the optical path length of the dye cell. The fluorescence density changes smoothly and roughly proportional to an exponential function. Since a contacted dye cell is used, no secondary fluorescence peaks appeared in the trace which indicates the absence of more than one picosecond pulse. A gradual reduction in pulse width was also noted with increase in operating voltage (Fig. 3).

4. Discussion

The laser power supply utilising the switch mode topology is found to be highly efficient compared to conventional linear types. The variation in time delay between the triggering of flash lamp pulse and the emission of laser pulse can be explained by considering the fact that the rate of pumping is inversely proportional to the rise time of pump pulse. So at higher operating voltages, the rise time of pump pulse is decreased and population inversion can be achieved more quickly. So the time delay is decreasing as flash lamp voltage increases.

The variation in laser pulse width is due to the nonlinear absorption of saturable dye taken in the variable path length dye cell. Near peak of the laser pulse where intensity is maximum, bleaching of the mode locker dye will be maximum. As a result that portion causes more transmission and lower intensity regions of the pulse causes less transmission. Pulse shortening occurs due to the increased absorption near the wings of the pulse. When the contacted dye cell is thicker the output will get contribution from the wings also. So the output pulse will have more width in comparison with that obtained when a thinner dye cell is used.

5. Conclusions

The series resonant converter used as the simmer current source of passively mode-locked Nd:YAG laser is working efficiently in comparison with other conventional linear power conversion techniques with respect to conversion efficiency and reduction in volume and weight. This scheme can also be used for fixed current simmer source to get a highly efficient and still more compact power supply.

The dependance of rise time of pumping pulse on the power supply charging voltage is the key factor for the observed time delay between the triggering of flash lamp pulse and the emission of laser pulses. The rate of pumping is depending on this rise time. Regarding the path length dependence of laser pulse width, to get thinner pulses the dye cell thickness should be minimum. Very short optical pulses are useful in many nonlinear optical experiments.

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