Q-SWITCHING OF NEODYMIUM YTTRIUM ALUMINIUM GARNET LASER VIA ACTIVE AND PASSIVE TECHNIQUES

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Dedicated to

my mother, Norimah Abd Mutalib

my father, Mohd Taib Mustafa

family members and friends

for your everlasting love and support

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ABSTRACT

Light modulation is important for increasing the laser output, but it needs proper technique and delicate nonlinear material which leads it to be costly. In contrast, the current demand is in favour to have a cheaper and user friendly laser. Therefore the aim of this study is to find the technique and alternative material in laser modulation. In attempt to achieve these goals a Nd:YAG rod was utilized as a gain medium and flashlamp as a pumping source. In an active technique, a Pockels cell containing Deuterated Potassium Dihydrogen Phosphate (DKDP) crystal was electrified at constant 3.28 kV high voltage. Variable pumped energy between 25 – 64 J was absorbed by the crystal to produce a maximum 60 mJ / 50 ns Q-switched pulsed energy. The performance of an electro-optically (EO) Q-switched Nd:YAG laser at transition line of $^4F_{3/2} \rightarrow {}^4I_{11/2}$ Stark levels based on DKDP crystal was demonstrated at various temporal delays in the range between 100 - 500 µs. In general, all the output energies of an EO Q-switched laser have similar parabolic normalized trend. However, the higher the input energy, the longer the temporal delay was realized to achieve the optimum output energy. The detailed results obtained from this study were 25.00 J / 240 µs, 30.25 J / 240 µs, 36.00 J / 240 µs, 42.25 J / 240 µs, 49.00 J / 250 µs, 56.25 J / 260 µs and 64.00 J / 290 µs. The results were then confirmed via spectroscopic analysis. Passively Q-switched technique was demonstrated by using a saturable absorber made of a multi-walled carbon nanotubes-polyethylene oxide (MWCNTs-PEO) film at two positions in the laser resonator to optimize its performance. With 88 J input energy, the Q-switched laser produced an optical signal pulse of 87 ns at position 1 (P1) and 115 ns at position 2 (P2). The conversion efficiency of the Q-switched laser with saturable absorber at P1 was about 0.43% with maximum output energy of 1.66 mJ and about 0.57% with maximum output energy of 1.60 mJ at P2. It can be summarized that P1 which was located nearer to the output coupler (OC) tends to be a better position for allocating MWCNTs-PEO saturable absorber in the laser resonator. Further exploration had been conducted by moving the OC for eight positions towards the saturable absorber at P1 with an increment of 10 mm at constant input energy of 88.36 J. It was found that the output energy increases between 1.54 - 1.68 mJ. In addition, the shortest pulse duration of 83.64 ns was obtained when the OC was at the closest distance to the saturable absorber. Further increase of the input energy to about 90 J tends to burn off the saturable absorber. In summary, Q-switched Nd:YAG laser modulation has been successfully achieved by using both active and passive techniques. The active technique requires optimization in temporal delay for higher output energy while the passive technique indicates that the MWCNTs-PEO has a high potential to be an effective saturable absorber.

ABSTRAK

Modulasi cahaya penting untuk meningkatkan keluaran laser, tetapi memerlukan teknik yang sesuai dan bahan tak linear yang sensitif dimana memerlukan kos yang tinggi. Sebaliknya, permintaan semasa memihak kepada laser yang lebih murah dan mesra pengguna. Maka, tujuan kajian ini adalah untuk mencari teknik dan bahan alternatif dalam modulasi laser. Bagi mencapai tujuan itu, rod Nd:YAG telah digunakan sebagai medium aktif dan lampu kilat sebagai sumber pengepaman. Untuk teknik aktif, sel Pockels yang mengandungi kristal Kalium Dihidrogen Fosfat Terdeuterat (DKDP) telah dielektrikkan pada voltan tinggi malar 3.28 kV. Tenaga pengepaman boleh ubah antara 25 - 64 J telah diserap oleh kristal menghasilkan tenaga denyutan bersuis-Q maksimum 60 mJ / 50 ns. Prestasi Nd:YAG laser bersuis-Q secara elektro-optik (EO) pada garis peralihan $^4F_{3/2} \rightarrow {}^4I_{11/2}$ aras Stark untuk kristal DKDP ini didemonstrasikan pada pelbagai tempoh tunda dalam julat 100 - 500 µs. Keseluruhannya, semua tenaga keluaran laser bersuis-Q EO mempunyai trend parabolik ternormal yang sama. Namun, semakin tinggi tenaga masukan, semakin panjang tempoh tunda untuk mencapai tenaga keluaran yang optimum. Keputusan terperinci yang diperolehi dalam kajian ini ialah 25.00 J / 240 µs, 30.25 J / 240 µs, 36.00 J / 240 µs, 42.25 J / 240 µs, 49.00 J / 250 µs, 56.25 J / 260 µs dan 64.00 J / 290 µs. Kemudian semua keputusan disahkan melalui analisis spektroskopi. Teknik bersuis-Q secara pasif telah didemonstrasikan dengan menggunakan penyerap tepu yang diperbuat daripada filem tiub nano karbon multi-dinding-polietilena oksida (MWCNTs-PEO) pada dua kedudukan dalam rongga laser untuk mengoptimumkan prestasinya. Dengan tenaga masukan 88 J, laser bersuis-Q menghasilkan isyarat denyutan optik 87 ns pada kedudukan 1 (P1) dan 115 ns pada kedudukan 2 (P2). Kecekapan penukaran laser bersuis-Q dengan penyerap tepu pada P1 ialah 0.43% dengan tenaga keluaran maksimum 1.66 mJ dan 0.57% pada P2 dengan tenaga keluaran maksimum 1.60 mJ. Ringkasnya, P1 yang terletak berhampiran pengganding keluaran (OC) merupakan kedudukan yang lebih baik untuk meletakkan penyerap tepu MWCNTs-PEO di dalam rongga laser. Penerokaan lanjut telah dilakukan dengan menggerakkan OC pada lapan kedudukan menghampiri penyerap tepu di P1 dengan penambahan 10 mm pada tenaga masukan malar 88.36 J. Didapati terdapat pertambahan tenaga dalam julat 1.54 - 1.68 mJ. Tambahan pula, tempoh denyutan paling singkat telah diperolehi apabila OC berada pada jarak paling hampir dari penyerap tepu. Peningkatan tenaga kepada kira-kira 90 J cenderung untuk membakar penyerap tepu. Ringkasnya, modulasi Nd:YAG laser bersuis-Q telah berjaya dicapai menggunakan kedua-dua teknik aktif dan pasif. Teknik aktif memerlukan pengoptimuman dalam tempoh tunda untuk tenaga keluaran yang lebih tinggi manakala teknik pasif menunjukkan bahawa MWCNTs-PEO mempunyai potensi tinggi sebagai penyerap tepu yang efektif.

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LIST OF SYMBOLS

N_1	-	Atoms in the upper state
N_2	-	Atoms in the lower state
B_{21}	-	Einstein's coefficient for stimulated emission
ρ_v	-	Spectral energy density of the photons
g(v)	-	Lineshape function
v	-	Density of excite atoms
n	-	Refractive index of medium
c	-	Speed of light
I/hv	-	Photon flux
σ_e	-	Stimulated emission cross section
g_1	-	The degeneracy factors
g_2	-	The degeneracy factors
I_p	-	Pump intensity
h	-	Planck's constant
σ_a	-	Absorption cross section
N_g	-	The ground state population
W_p	-	The pumping rate
λ_p	-	The pumping wavelength
λ_L	-	The lasing wavelength
τ_f	-	Fluorescent lifetime
v_p	-	Pump frequency
v_L	-	Laser frequency

$\varrho(\nu)$	-	Radiation density per unit frequency
k	-	Boltzmann's constant
ν_o	-	Laser central frequency
L	-	Length of the resonator
W	-	Energy stored
λ_0	-	Laser's central wavelength
η	-	Laser's slope efficiency
δ	-	The insertion loss
E_1	-	Free running mode
E_2	-	Pockels cell output energy
E_3	-	Q-switched output energy
G	-	Percentage rate of the output energy
$V_{\lambda/4}$	-	Quarter wave voltage
$V_{\pi/2}$	-	Half wave voltage
γ	-	Electro-optic factor
E_v	-	Valence band
E_c	-	Conduction band
a_{abs}	-	Effective beam area
α_o	-	Absorption coefficient
I_s	-	Absorption intensity
t_d	-	Temporal delay

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CHAPTER 1

INTRODUCTION

1.1 Overview

The accomplishment of humankind in generating high intense light known as LASER (Light Amplification by Stimulated Emission of Radiation) in the early nineteen sixties leads the discovery of much scientific knowledge regarding light technology. The laser light possesses its uniqueness in terms of monochromatic, coherent, high intensity and collimation. The development of laser still in progress as the competition in building high power laser with low energy consumption as well as the laser system itself are continuously changing. Not to forget, the inventors also keep on exploring and reveal the best one to be used in the laser development as nowadays trend tends into tiny, simple and reliable devices.

High power laser which usually comes from high voltage energy sometimes meet the limits as it is too dangerous to handle and require high costs to be implemented. Q-switch systems which consume less energies yet very effective and simple finally turn out as an alternative way in generating laser beam amplification. High output pulse energy with high peak power is produced during the formation of Q-switched light. The capability of the system to generate large amount of energy within a period of time can be achieved by altering its spectral or temporal output of a laser either in the cavity resonator or outside. The light properties such as intensity, wavelength and polarization can be modified by various techniques of light modulation. Both actively and passively Q-switching techniques can be designed to produce Q-switched, mode-locked, or Q-switched and mode-locked output.

In this research, the modulation of light in Neodymium Yttrium Aluminium Garnet (Nd:YAG) laser was executed via active and passively Q-switched techniques. Pockels cell contained electro-optic DKDP crystal and carbon nanotubes were employed as a switcher for active and passive technique respectively. Flashlamp pump source, filled with Xenon gas was used as an optical pumping and the flashlamp power supply was based on the series mode triggering technique. The Nd:YAG crystal was used as laser gain medium in sequence to generate population inversion since it can produce more laser lines in the near-IR spectral region. Two coated mirrors placed in between the gain medium to provide feedback of the light. The performance of Q-switched Nd:YAG laser for active and passively techniques pumped by flashlamp was investigated.

1.2 Problem Statement

Currently Nd:YAG laser has been modulated based on time delay between flashlamp signal and input trigger pulse of Q-switch system at fixed input voltage. Therefore the output power of the laser entirely depends on the population inversion phenomena. The Q-switch pulse must be given “some time” after the flashlamp trigger signal ordered pumping power to the flashlamp, so that laser could be emitted to let the optical resonator build gain. High amount of population inversion is reached if we controlled and manipulated the temporal delay. The drawback with such system is that the efficiency subsequently the performance of the laser system is hard to be determined. Furthermore the Q-switched laser system is relied on a nonlinear material to conduct the switching. The problem with the nonlinear material is hard to fabricate and some of them are hygroscopic. Thus in operating Q-switched laser is better to consider an alternative material to replace the nonlinear material. The employment of carbon nanotubes based saturable absorber (CNTs-SA) has high potential for laser light modulation techniques recently. It is a competent method nowadays as it promises a simple cavity design, reliable and low cost fabrication. Thus, nowadays researchers pay much attention focusing on material like CNTs-SA as a light switcher. The capability of this material in generating Q-switching and mode-locking laser had made it very tremendous method for light modulation. Even though much works on the CNT as passive Q-switch saturable absorber has been addressed on diode (Feng *et al.*, 2013; Wang *et al.*, 2013; Chu *et al.*, 2014) and fiber optic laser (Nicholson *et al.*, 2007; Dong *et al.*, 2010; Dong *et al.*, 2011; Qu *et al.*, 2012) but yet very rare its application on flashlamp pumped neodymium doped YAG crystal have been established. Therefore, we intend to use and observe its characteristics toward laser light modulation especially in flashlamp pumping source. In addition, the intention of this work is also to explore the suitability and reliability of applying CNTs based saturable absorber in generating Q-switched laser by using flashlamp pumping source. The enthusiasms regarding this work proceed with further cavity compactness in attempt to gain optimization of the output Q-switched laser. To the best of our knowledge, this is the first multi-walled CNTs-SA has been reported on the flashlamp pumping Nd:YAG laser. Hence there are two major works need to be done, to tune the delay based on voltage variation and identify the appropriate material for switching.

1.3 Research Objective

The aim of this research is to optimize the output energy for Q-switched Nd:YAG laser based on active and passive techniques. This is accomplished by the following tasks:

i. Constructed free-running pulsed Nd:YAG laser
ii. Developed an optical resonator configuration for both active and passively Q-switched laser by employing electro-optic DKDP crystal and MWCNTs-SA
iii. Optimized the Q-switched laser output for both techniques
iv. Characterized and analyzed the Q-switched laser performance

1.4 Research Scope

In this study, Nd:YAG laser rod was employed as a gain medium. It was pumped by xenon flashlamp. A linear cavity was designed and operated in free running mode. Then, the laser beam was modulated into Q-switched system. Two techniques were conducted that are active and passive methods. In active method, DKDP crystal was used as a Pockels cell and an external source was provided to change its polarity. Active Q-switched was established by supplying 3.28 kV longitudinally. In passive method, multi-walled carbon nanotubes polyethylene oxide film (MWCNTs-PEO) was fabricated to be implemented as a saturable absorber. The saturable absorber was placed in two positions to optimize the switching technique. Both switching were characterized based on the pumping energy which varied in the range 25 - 88 J.

1.5 Thesis Outline

This thesis consists of five chapters. Chapter 1 illustrates the introduction part which covers the basic and reasons why this work is carried out, and mainly a brief elaboration about the whole project. It also contains the problem statement, the research objectives and the scope of study.

The review and history of Q-switching technique are discussed in Chapter 2. This covered on the fundamentals and basic theories. The basic principle of laser operation, Nd:YAG laser properties, types of optical pump source, and Q-switching technique for both active and passively methods are all explained in this chapter.

The implementation methods for both active and passively Q-switched are described in Chapter 3. All the material, equipment and technique employed in this research are explained in this chapter. The fabrication of MWCNTs-PEO film is also well clarified.

The results obtained in this work are analyzed and discussed in detail in Chapter 4. The Q-switched laser performances in terms of laser output energy, laser pulse width, laser spectrum and laser beam for both active and passive techniques are well evaluated and discussed in this chapter. This chapter also highlights the method approached to optimize the Q-switched output laser. For active method, the optimum delay of flashlamp trigger and fast high voltage switch are recognized by tuning the time delay with respect to the input energy. While for passive method, the laser output is enhanced by determining the best position to place the CNTs-SA.

Finally, the conclusions of this research and the recommendations for future work are suggested in Chapter 5.

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