wjert, 2020, Vol. 6, Issue 5, 190-199. *Original Article* ISSN 2454-695X

World Journal of Engineering Research and Technology

WJERT

www.wjert.org SJIF Impact Factor: 5.924

SIMULATION OF SATURABLE ABSORBER MATERIAL POPULATION DENSITY EFFECT ON PULSE CHARACTERISTICS OF PASSIVELY Q-SWITCHING YB^{+3} DOPED FIBER LASER

***Dunya Saad Hussein and Dr. Abdul-Kareem Mahdi Salih**

Physics Dep. - College of Science - Thi-Qar University, Thi-Qar, Iraq.

Article Received on 20/07/2020 **Article Revised on 10/08/2020** **Article Accepted on 30/08/2020**

***Corresponding Author**
Dunya Saad Hussein
Physics Dep. - College of Science - Thi-Qar University, Thi-Qar, Iraq.

ABSTRACT

Saturable absorber material (SAM) population density effect on the pulse characteristics of passively Q-switching Yb^{+3} doped fiber laser has been simulated. Cr^{+4}:YAG used as a SAM in the study. Software computer program buildup in this study for numerical solving of Rate equations model by Runga Kutta –Fehlberg method. The results shows the increasing of saturable absorber material population density lead to increasing each of initial and final values of population inversion density, maximum photons number, and pulse energy. While on another hand lead to decreasing each of rising time and falling time of pulse.

KEYWORDS: Passive Q-Switched, Yb^{+3} Doped Fiber Laser.

INTRODUCTION

In recent times, fiber lasers have been a field of intense research and development due to its diverse path breaking applications in industries and medicine owing to high beam quality, ease of delivery and high power feasibility.[1] All fiber construction provides inherent robustness and relative compactness. Also keeping the light constrained to a waveguide with no open-air propagation or alignment considerations improves both the short and long term stability of the system. While simultaneously eliminating many potential noise sources.[2] High output powers have been achieved by solid-state optical fiber laser amplifiers. The model for population dynamics of Yb ions is simpler as it can be modeled using only two energy states, the ground state and one excited state manifold.[3] Such materials with their simple electronic structure having only two manifolds ($^2F_{7/2}$ and $^2F_{5/2}$) avoid unwanted nonlinear processes such as excited state absorption (ESA) and up-conversion. In addition, a smaller Stokes shift between the absorption and emission lines.[4] For obtain high laser pulse power, passively Q-switching technology based on saturable absorbers (SAs) is widely used with in doped fiber laser.[5-7] Asaturable absorption as Cr^{+4} :YAG widely used a passivily element inside the optical cavity of passive Q-switching technique, can be represented by a simple energy-level diagram such as shown in Fig. (1).[8]

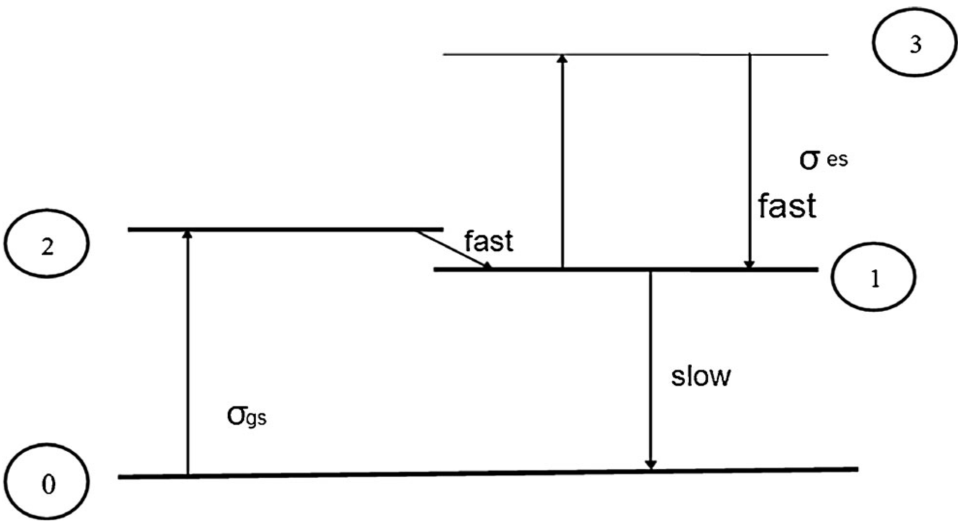

Fig. (1): energy level diagrams for Cr^{+4}:YAG ions.[8]

2. Theory

Coupled rate equations model.[9] has been used to simulation of saturable absorber material population density effect on pulse characteristics of passively Q-switching Yb^{+3} doped fiber laser as the following:

$$\frac{d\phi(t)}{dt} = \frac{\phi(t)}{\tau_r}[2\sigma_{am}l_{am}N(t) - 2\sigma_{gs}l_{sa}N_{gs}(t) - 2\sigma_{es}l_{sa}N_{es}(t) - (\ln(\frac{1}{R}) + L_{loss})] \quad (1)$$

$$\frac{dN(t)}{dt} = R_P - \gamma c\sigma_{am}\phi(t)N(t) - \frac{N(t)}{\tau_{am}} \quad (2)$$

$$\frac{dN_{gs}(t)}{dt} = \frac{N_{es}(t)}{\tau_{sa}} - 2\sigma_{gs}l_{sa}\phi(t)N_{gs}(t)/\tau_r \quad (3)$$

$$\frac{dN_{es}(t)}{dt} = -\frac{N_{es}(t)}{\tau_{sa}} + 2\sigma_{gs}l_{sa}\phi(t)N_{gs}(t)/\tau_r \quad (4)$$

Where: ϕ is the photons density, τ_r is the round –trip transit time $(2L_r/c)$, L_r is the cavity optical length, c is the speed of light, l_{am} is the fiber length (active medium), N_{am} is the population inversion density of active medium, σ_{gs} is the ground-state absorption cross section of SAM , l_{sa} is the length of SA M , N_{gs} is the population of S.A.M. ground state , N_{es} is the population of SAM exited state, σ_{es} is the excited-state absorption cross Section of SAM , R is the geometric mean of the cavity ($R=(R_1R_2)^{1/2}$), R_1,R_2 the mirrors reflectivity, L_{loss} is the dissipative optical losses for each round –trip. N is the population inversion density, R_p is the optical pumping rate , γ is a factor in population reduction factor equals 1 for 4 levels and 2 for 3 level of active medium system. τ_{sa} is the lifetime of the SAM, τ_{am} is the fluorescence lifetime of the upper laser level.

The build-up time of Q-switched laser pulses is generally very short compared the fluorescence lifetime of the upper laser level and the time of pumping rate , then it is possible to neglect the spontaneous decay of the upper laser level and the pumping rate during pulse generation,[10,11] So the lifetime of the SAM it is very long compared the build-up time of Q-switched laser pulses,[10] then can be rewrite Eq.(2) , Eq.(3), and Eq.(4) as the bellow expressions respectively:

$$\frac{dN(t)}{dt} = -\gamma c\sigma_{am}\phi(t)N(t) \tag{5}$$

$$\frac{dN_{gs}(t)}{dt} = -2\sigma_{gs}l_{sa}\phi(t)N_{gs}(t)/\tau_r \tag{6}$$

$$\frac{dN_{es}(t)}{dt} = 2\sigma_{gs}l_{sa}\phi(t)N_{gs}(t)/\tau_r \tag{7}$$

At the initial time, the photons density inside the cavity optical is small, so most of saturable absorber molecules are in the ground state (N_{gs}), then can be regards $N_{gs} \approx N_{sao}$ or $N_{es} \approx 0.0$, where $(N_{sao} = N_{gs} + N_{es})$ is the total number of molecules of SAM.

Also at the initial time, the SAM absorption activity is very high, can be regards $\frac{d\phi}{dt} \approx 0.0$ in Eq.(1) , then the initial population inversion density value (N_0) for laser medium can be predicted from Eq.(1) as the following:

$$N_o = [2\sigma_{gs} l_{sa} N_{sao} + (\ln(\frac{1}{R}) + L_{loss})]/2\sigma_{am} l_{am} \tag{8}$$

When the number of photons inside the optical laser cavity reaches to maximum value (peak of pulse), most SAM population in the excited state (N_{es}), can be regards $N_{es} \cong N_{sao}$ ($N_{ag} \cong 0.0$); Then the absorption activity of the SAM is very low at this time. Can be considering $\frac{d\phi}{dt} \approx 0.0$, The threshold population inversion N_{th} can also be predicted from Eq.(1) as follows:

$$N_{th} = [2\sigma_{es} l_{sa} N_{es}(t) + (\ln(\frac{1}{R}) + L_{loss})]/2\sigma_{am} l_{am} \tag{9}$$

The pulse duration (τ_p) can be approximated by the following equation[12]

$$\tau_p = \tau_c \frac{N_o - N_f}{N_o - N_{th} - N_{th} \ln(\frac{N_o}{N_{th}})} \tag{10}$$

Where is the optical laser cavity lifetime given by the expression :

$$\tau_c = \tau_r /(\ln(\frac{1}{R}) + L_{loss}) \tag{11}$$

The energy of output laser pulse can be approximated by the following equation[13]:

$$E_{out} = (\frac{N_o - N_f}{\gamma}) h\upsilon\eta_c \tag{12}$$

Where h is Blank constant, υ is the laser frequency, η_c is the output coupling efficiency, it is given by the expression.[14]

$$\eta_c = (\frac{N_o - N_f}{N_o})$$

3. RESULTS AND DISCUSSION

Software computer program buildup in this study for solve the set of coupling rate equations model (Eq.s 1,5,6 and 7) numerically by Runga Kutta –Fehlberg method. Simulation of saturable absorber material population density effect on the pulse characteristics of passively Q-switching Yb^{+3} doped fiber laser has been performed, using Cr^{+4}:YAG as a passive Q-switching. The input data has been used in simulation reported as the following.[15,16]

: $\sigma_{am} = 0.241\times 10^{-21} cm^2$, $\sigma_{ag}= 8.75\times10^{-19} cm^2$ $\sigma_{es} = 2.25\times10^{-19} cm^2$, $\tau_{sa} = 2.9\times10^{-4} s$,

$\tau_{am} = 0.951\times10^{-3} s$, $l_{am} = 250cm$, $l_r = 300cm$, $R_2 = 0.925$, $R_1 = 0.995$, $\lambda = 1040nm$, $\gamma = 2$.

Fig.(2) shows an increase in the initial value of population inversion density of ions doped the optical fiber as an active medium(AM) with the increase of population density of SAM. The study explains that related to a decrease in the laser photons density inside the optical cavity due to the increase in the absorption activity of SAM, that lead to less ions-photons interaction to be caused ions accumulation in upper laser level as population inversion density in optical fiber.

Fig.(3) shows the temporal behavior of the photons loss in terms of population density of SAM, at the initial time of pulse generation, the losses characterized by high initial value for the high saturable absorber population density, so continues to decrease with the pulse building time until it reaches a stable state. After the pulse generation and released, we get the inversely behaviuor of losses. The study interpreted this behavior to occurrence the optical bleaching state at shorter time whenever increasing of population density of SAM. This discussion enhancements the profile in Fig.(2).

Fig.(4) shows the temporal behavior of the population inversion density of the ions doped the optical fiber in terms of different values of population density of SAM. At the initial time of pulse generation, the population inversion density characterized by high initial value when high saturable absorber population density, so continues to decrease with the pulse building time until it reaches a stable state. After the pulse generation and released, we get the inversely behaviuor of population inversion density. The study interpreted this behavior to increasing of decay rate of upper laser ions after threshold value of population inversion.

Fig. (5) Shows the increments of threshold population inversion density whit the increment of population density of SAM. The study give reason to increment which occurred in initial population inversion density which is discussed in Fig.(2).

Fig. (6) shows the temporal behavior of passive Q-switched pulse for different values of population density of SAM. The Fig. appear the Amplitude of pulse proportional with saturable absorber population density. The results to be comport with the results in Fig.(2). The study explains the behavior to increase in the initial population inversion.

Fig. (7) shows the effect of population density of SAM on the its absorption activity, no distinguishable difference at initial time of pulse generation, but the activity absorption difference being more distinguishable after the pulse generation. The study interprets the results due to occurrence the optical bleaching state at advanced time whenever increasing of population density of SAM.

Fig. (8) shows an increase in the maximum value of the pulse photons density with an increase in the population density of SAM. The study explains that related to the increment of initial value of the population inversion density of the optic fiber ions. Fig. (8) complementary to the result or discussion of Fig.(2).

Fig. (9) shows the increase the difference between the initial and final value of the density of the population inversion. It is worth noting that in despite of the increasing in final value of population inversion density as shown in Fig. (10), the difference between the initial and final value still increase. The increase in final value less than the increase in the initial value, which made increment in difference leads to an increase in the maximum value of the pulse photons.

The increase in the maximum value of the pulse photons means an increase in the released energy with the emission of the pulse. This result appear in Fig. (11).

Fig. (12) shows a decrease in the duration of the pulse duration with the increase in the population density of SAM. The study refer that for two reasons. The first is the decrease in the pulse rise time, as shown in Fig. (13) because of the rapid release of the pulse , and the second is the decrease in the pulse falling time as shown in Fig. (14) because of the rapid decay of the pulse.

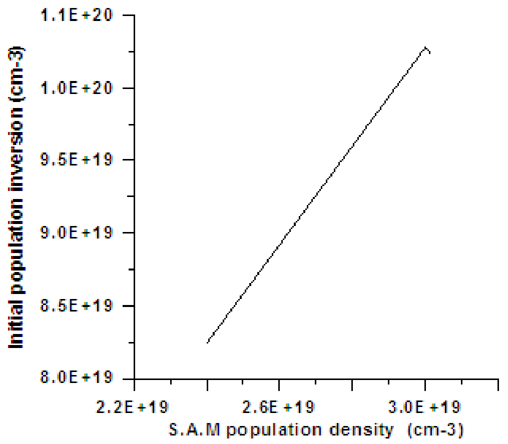

Fig. (2): Initial population inversion as a function of SAM population density.

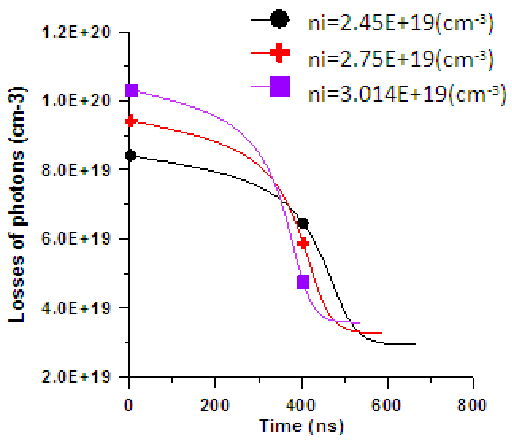

Fig. (3): Profiles of losses of photons a function of time.

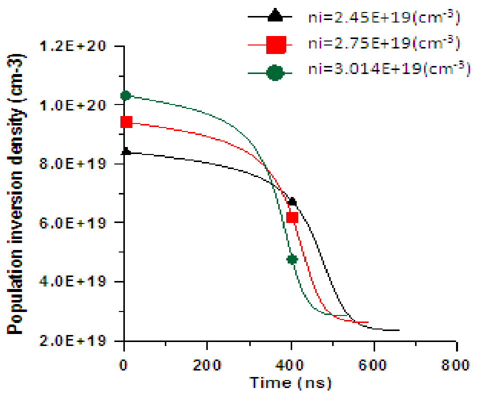

Fig. (4): Profiles of population inversion density as a function of time.

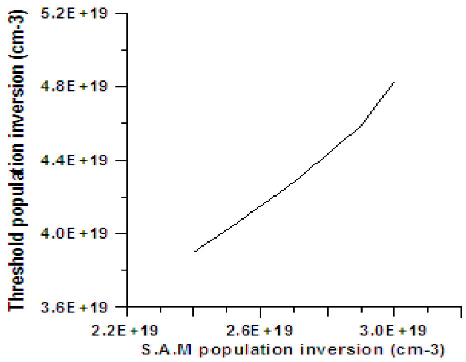

Fig. (5): Threshold population inversion as a function of SAM population density.

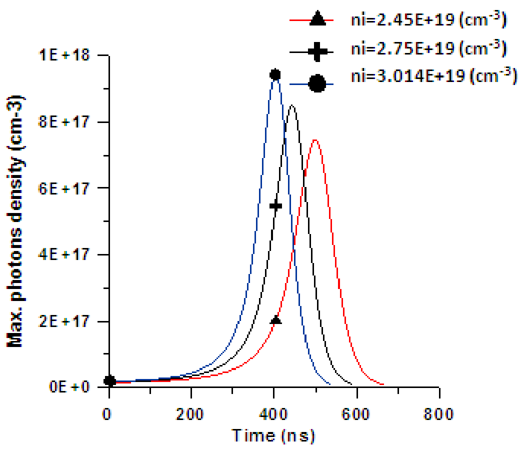

Fig. (6): Profiles of max. Photons density as a function of time.

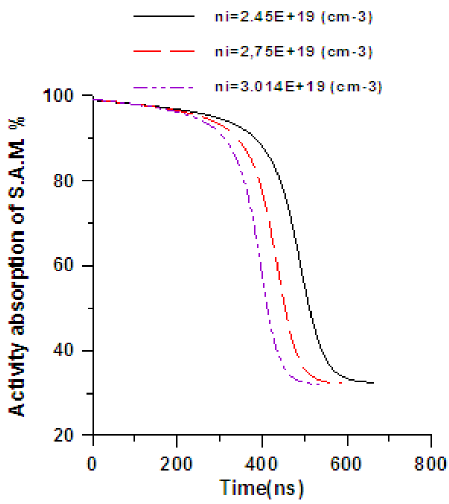

Fig. (7): Activity absorption of SAM for different SAM population density.

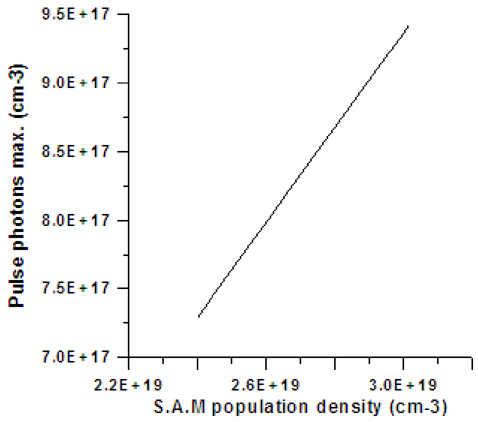

Fig. (8): Pulse photons max as a function of SAM population density.

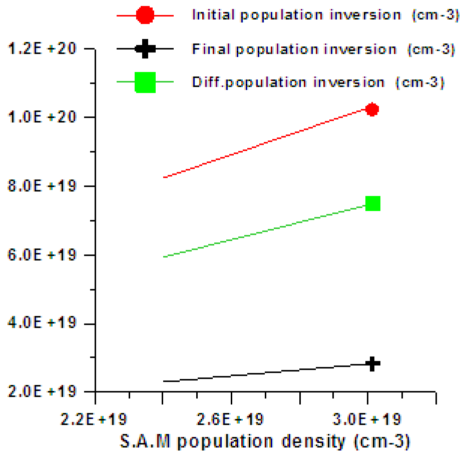

Fig. (9): Difference population inversion as a function of SAM population density.

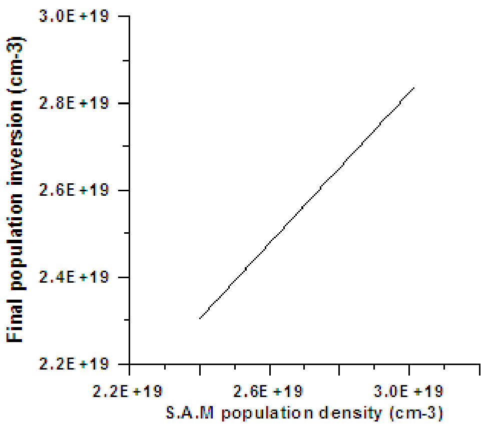

Fig. (10): Final population inversion as a function of SAM population density.

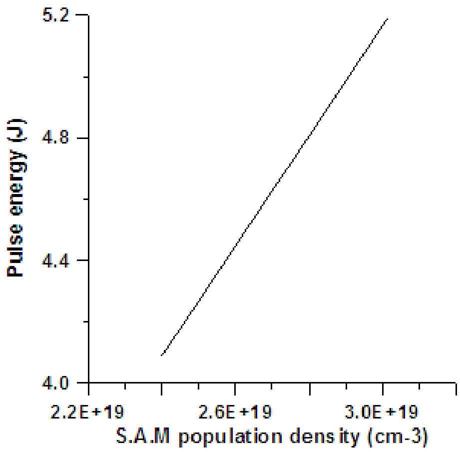

Fig. (11): Pulse energy as a function of SAM population density.

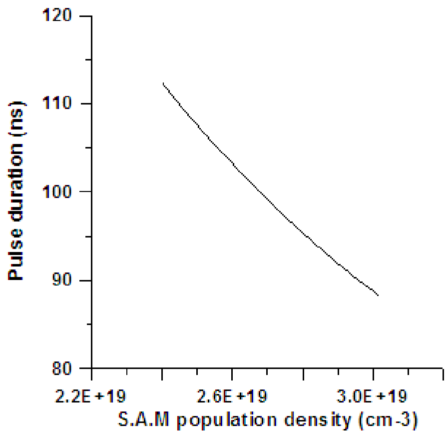

Fig. (12): Pulse duration as a function of SAM population density.

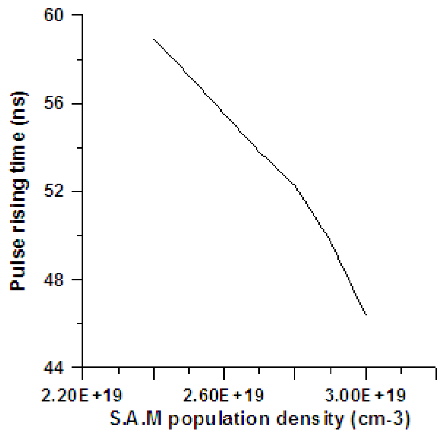

Fig. (13): Pulse rising time as a function of SAM population density.

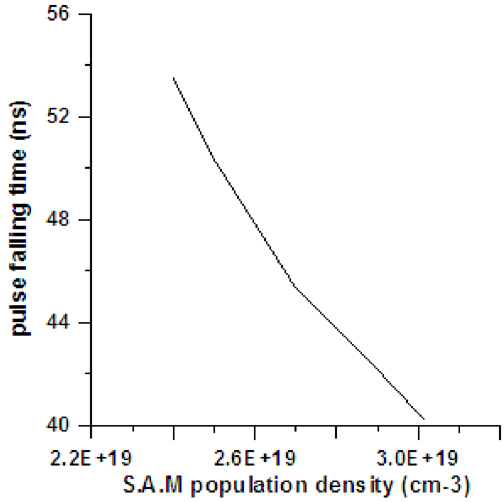

Fig. (14): Pulse falling time as a function of SAM population density.

4. CONCLUSIONS

The increasing of population density of SAM lead to increasing of initial and final values of population inversion density, maximum photons number an pulse energy. While on another hand lead to decreasing of pulse duration because the decrease of rising time and falling time of pulse.

REFERENCES

1. U. Chakravarty, S. Gurram, A. Kuruvilla, B. N. Upadhyaya, and K. S. Bindra, "Short pulse generation in active Q-switched Yb-doped all fiber laser and its amplification," Opt. Laser Technol., February 2018; 109: 186–192. doi: 10.1016/j.optlastec.2018.07.074.
2. A. Scott, "Construction and Passive Q-Switching of a Ring- Cavity Erbium-Doped Fiber Laser Using Carbon Nanotubes as a Saturable Absorber," Theses, Rose-Hulman Institute of Technology, United States, 2017.
3. D. Drake, J. Gopalakrishnan, T. Goswami, and J. Grosek, "Simulation of optical fiber amplifier gain using equivalent short fibers," Comput. Methods Appl. Mech. Eng., 2020; 360: 112698. doi: 10.1016/j.cma.2019.112698.
4. S. Paul et al., "Efficient diode pumped Yb : Y 2 O 3 cryogenic laser,", 2019; 1–5.
5. L. Fan et al., "Influence of few-layer WS2 and mono-layer WS2 on passively Q-switched ytterbium-doped fibre lasers," Laser Phys., 2019; 29(7): doi: 10.1088/1555-6611/ab20c2.

6. D. Z. Mohammed and A. AL-Janabi, “Large diameter coreless fiber as a saturable absorber for erbium doped fiber laser cavity based on multimode interference,” Opt. Fiber Technol., 2019; 50: 212–215. doi: 10.1016/j.yofte.2019.04.002.
7. Y. Chen et al., “Mechanically exfoliated black phosphorus as a new saturable absorber for both Q-switching and Mode-locking laser operation,” Opt. Express, 2015; 23(10): 12823. doi: 10.1364/oe.23.012823.
8. A. Nady et al, “Theoretical and experimental studies on a Q-switching operation in an erbium-doped fiber laser using vanadium oxide as saturable absorber,” *Laser Phys.*, 2018; 28(8): 715.
9. Dunya Saad Hussein, Abdul-Kareem Mahdi Salih," Simulation of fiber length effect on the pulse characteristics of passively Q-switching Yb^{+3} doped fiber laser", Vol. 83:, *TEST Engineering and Management*, March/April, 2020.
10. A. M. Salih, “Numerical analysis of molecules intersystem crossing effect on a passively Q- switched laser pulse characteristics”, Iraqi Journal of Physics, 2012; 10(17): 1–6.
11. Y. F. Chen, J. L. Lee, H. D. Hsieh, and S. W. Tsai, “Analysis of passively Q-switched lasers with simultaneous modelocking,” IEEE J. Quantum Electron., 2002; 38(3): 312–317. doi: 10.1109/3.985573.
12. C. Chang, J. Chang, and Y. Kuo, “Optical Performance of Cr : YSO Q-switched Cr : LiCAF and Cr : LiSAF Lasers,”, 2002; 4914: 498–509.
13. R. He, J. R. Vázquez De Aldana, and F. Chen, “Graphene Q-switched laser operation in Nd: YVO4 cladding waveguides produced by femtosecond laser writing,” Adv. Solid State Lasers, ASSL, 2014; 9(7–9): 2014: doi: 10.1364/assl.2014.am5a.3.
14. Y.K. Kuo, “Numerical study of the Cr:YSO switched ruby laser,” Opt. Eng., 2001; 40(9): 2031. doi: 10.1117/1.1397302.
15. D. Savastru,R. Savastra, S. Miclos, and I. Lancranjan." Numerical analysis of Passively Q-switched Er and Yb Doped fiber Laser”, PIERS Proceding, Stokholm, Sweden, 2013; 12(15): 1776-1780.
16. Dan Savastru, Sorin Miclos, and Ion Lancranjan. "Theoretical analysis of passivily Q-switched erbium doped fiber laser”, Neconventional Technologies review, Romania, 2012.