# Pulse Width and Stability Dependence of Passively Q-Switched Erbium-Doped Fiber Laser on MWCNTs' SA Concentration

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**Abstract**

The concentration effect of multi-walled carbon nanotubes (MWCNTs) dispersed in polyvinyl alcohol (PVA) polymer matrix has experimentally investigated as a saturable absorber (SA) to stabilize the Q-switching performance of ring cavity erbium-doped fiber laser (EDFL). The output pulse width was reduced from 4.6 to 4.4 down to 4 µs corresponding to an increase in MWCNTs' SA concentration from 0.25 to 0.5 up to 0.75 wt%. The Q-switched EDFL output was very stable as the MWCNTs' concentration increased from 0.5 to 0.75 wt%, while the lowest MWCNTs concentration 0.25% showed a noticeable instability.

**Keywords**: Multi walled carbon nanotubes, fiber lasers, passive saturable absorbers, Q-switched

# اعتمادية عرض النبضة و استقرارية ليزر الليف الضوئي المشوب بالاريبيوم ذي مفتاح عامل النوعية على تراكيز انابيب الكاربون النانوية متعددة الجدران المستخدمة كمادة امتصاص مشبع

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**الخلاصة**

إن تأثير تركيز الأنابيب النانوية الكربونية المتعددة الجدران **(MWCNTs)** المخلوطة في بوليمر كحول بولي فينيل **(PVA)** قد تم دراسته عمليا لاختبار الاستقرار في أداء ليزرالليف الضوئي المشوب بالإربيوم ذي مفتاح عامل النوعية. النتائج التي تم الحصول عليها تم فيها تخفيض عرض نبضة الليزر الخارج من 4.6 إلى 4.4 **µs** إلى 4, وذلك نتيجة زيادة تركيز **MWCNTs** من 0.25 – 0.75٪. واظهرت النتائج ان زيادة تركيز **MWCNTS**الى 0.75% ابدى استقرار واضحا ،بينما أظهر تركيز **MWCNTs** الأدنى 0.25٪ عدم استقرار ملحوظ.

**الكلمات المفتاحية:** ليزر الليف الضوئي، انابيب كاربونية متعددة الجدران، ممتص مشبع ،ليزر ذي مفتاح عامل النوعية

## 1. Introduction

Q-switched erbium-doped fiber laser (EDFL) enables to generate short giant pulses of light [1,2], which found many potential applications such as remote sensing, range finding, medicine, material processing, and telecommunications [3-7]. Passive and active Q-switching methods are widely used to modulate the Q-factors in EDFL cavity to generate high energy pulses within short pulse widths [8-11]. Due to their various advantages including compactness, reasonable cost, flexibility and simplicity of incorporation within the resonator, passively Q-switched EDFLs have attracted much attention compared with active Q-switching techniques [12]. The most familiar materials that used as saturable absorbers (SAs) are the semiconductor saturable absorber mirror (SESAM) [13] and the transition metal-doped crystals [14]. However, the fabrication of these SAs is relatively time-consuming and cost-ineffective as well as their inherited high insertion losses.

Recently, nano materials-based saturable absorbers have been simply fabricated to allow all- fiber pulsed EDFL demonstration, such as topological insulator nano particals [15,16], graphene [17,18], graphite [19], charcoal nano material [20], graphene oxide and carbon black nano powders [21]. Among those nano materials, carbon nanotubes (CNTs) have attracted much attention to be used as saturable absorbers [22,23] because of their unique features. These features include, low saturation intensity, high damage threshold, fast recovery time, wide absorption range, low cost, ease of fabrication and good compatibility with optical fiber [23-25]. Generally, CNT materials can be categorized into three major types: single-walled (SWCNTs), double-walled (DWCNTs) and multi-walled carbon nanotubes (MWCNTs) depends on the number of layers of rolled up carbon sheet constructing the coaxial cylindrical tube [26]. MWCNTs exhibit advantages over SWCNTs, such as ease of mass production, low product cost per unit, and enhanced thermal and chemical stability.

Many techniques have been employed to fabricate CNTs-based SAs such as spray-coating on quartz substrate [27] or directly growing on fiber ends [28] or even in a solution [29]. However, these techniques are simple but they produce high losses in the laser cavity due to presence of bundled and entangled carbon nanotubes which severely affect the stability of EDFL output [30]. Fortunately, it has been found that dispersing CNTs in a polymer matrix, such as polyvinyl alcohol (PVA) is the best solution to overcome aggregation problems and accordingly reducing the insertion loss of the SA. Practically, CNTs-PVA saturable absorbers for Q-switched EDFL have showed a remarkable interested for researchers over the last few years.

In this work, we comprehensively investigated the effect of concentration of MWCNTs dispersed in PVA polymer matrix, on the output pulse width and stability of passively Q-switched erbium doped fiber laser (EDFL) with a ring cavity. The MWCNTs SA thin film is sandwiched between two fiber connectors through FC/PC adapter. The optical spectrum, pulse trace, pulse repetition rate (PRR), output power and output energy for three different MWCNTs concentrations are characterized to the Q-switched EDFL. The optimal value for MWCNTs' concentration is pointed out for shortest pulse width and much stable Q-switching operation for EDFL. A focused study on stable and shorter Q-switched pulse generation involving MWCNTs-PVA SA will broadly benefit to the utilization of the MWCNTs SA for use in many other low-cost photonic devices.

## 2. Methods

In this work, MWCNTs (Nanoshel) with diameter 20-30 nm, length of 3-8 µm and purity of 95% were used. MWCNTs features were revealed with the SEM image as it is illustrated in figure 1. The MWCNTs were functionalized by using sodium dodecyl sulfate (SDS) surfactant in order to be easily dispersed in water. 2000 mg of SDS was added to 200 ml of deionized water and mixed with magnetic stirrer for about 15 minutes. Then 125 mg of MWCNTs were added to the solution and nicely mixed. The resultant solution was sonicated for an hour in order to allow homogenous dispersion of MWCNTs and then centrifuged at 1000 rpm for 30 minutes to remove all the large and unwanted aggregated particles of MWCNTs. The final suspension can stay usable for few weeks to be added to PVA solution.

The PVA solution was prepared by mixing 0.5 g of PVA in 200 ml of deionized water with a warm plate magnetic stirrer at 60 $C^0$ for 30 minutes till the PVA was completely dispersed. The MWCNTs suspension is added to PVA solution with three different ratios that contain different MWCNTs' concentrations which are 0.25 wt%, 0.5 wt% and 0.75 wt%. The resultant three mixtures were then ultra-sonicated for an hour to obtain the required viscosity to form thin films. 5 ml of the resultant MWCNTs-PVA mixtures was spread carefully in well covered petri dishes and left to be dried in room temperature for about 96-120 hours and then to be used as independent SAs.

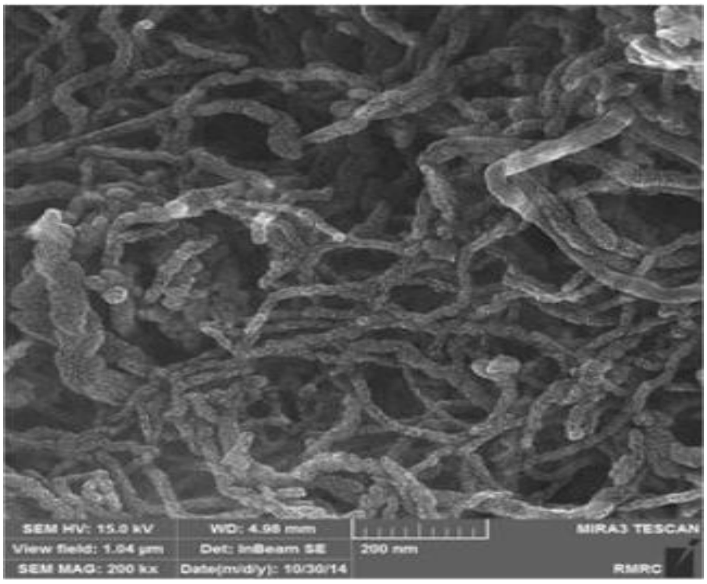


**Figure (1)** The SEM image of MWCNTs.

## 3. Experimental Setup

The experimental setup of the proposed Q-switched EDFL is illustrated in figure 2. The ring cavity comprimises of an active medium of 2 m length erbium- doped fiber (EDF) (Liekki ER80-4/125) with Er-ion concentration of 3000 ppm pumped via 980/1550 nm wavelength division multiplexer (WDM) by a 975 nm diode laser (Thorlabs) with maximum power of 330 mW. The EDF has an 80 dB/m absorption ratio at 1530 nm, core numerical aperture of 0.2 and mode field diameter of 6.5 µm at 1550 nm. A polarization independent isolator (ISO) was used to allow laser unidirectional circulation inside the cavity and to prevent back reflection. The polarization of the circulated light in the EDFL cavity was detuned by a polarization controller (PC). A 1×2 optical coupler (OC) was spliced within the ring cavity to allow 90% feedback ratio and 10% output ratio. The total cavity length was only 8 m. All the optical individual parts of the ring EDFL cavity were spliced with the automatic mode of the fusion splicer (Fujikura FSM-60S) to minimize the total losses inside the cavity as much as possible. The previously prepared MWCNTs-PVA thin films were integrated independently inside the cavity by cutting a piece of a diameter of 1 mm from the prepared thin film and then sandwiched between two fiber's connecters end using FC/PC adapter. The scattering losses were reduced by adding index matching gel (Thorlabs) with refractive index n= 1.4378 at 1550 nm on the end face of the fiber connecter where the saturable absorbers would be placed. The insertion losses of the three different MWCNTs' concentration SAs (0.25, 0.5 and 0.75 wt%) were measured at 1550 nm and they were 1.83, 1.86 and 1.86 dB respectively. In this work, we focus on evaluating the temporal and spectral characteristics of EDFL output by varying concentration of MWCNTs' SA and keeping the other parameters of the EDFL ring cavity unchanged during experiment. The output spectrum was measured with an optical spectrum analyzer (Yokogawa AQ6370C) at a resolution of 0.02 nm. The output pulses train were monitored using 5 GHz InGaAs FC/PC coupled photodetector (Thorlabs) connected to 500 MHz oscilloscope (Tektronix DPO 3052).

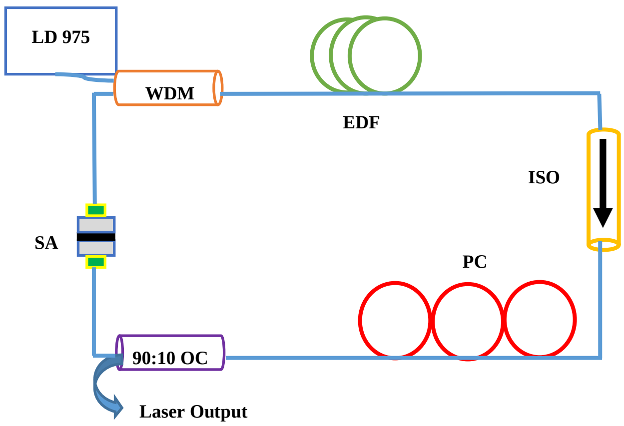


**Figure (2)** The schematic configuration of the proposed Q-switched erbium-doped fiber laser.

## 4. Results and Discussion

The laser has started Q-switching for the first concentration (0.25 wt% MWCNTs' SA) at low diode pump power of 25 mW. Figure 3 shows the oscilloscope trace of the Q-switched pulse trains at pumping threshold. The pulse width was 23 µs and the pulse repetition rate (PRR) was 5.5 KHz. The central wavelength of the output optical spectrum was not stable, fluctuating and multi-peaks have appeared as it is shown in figure 4. The average output power and the pulse energy as a function of the pump power are presented in figure 5. The pulse width and the pulse repetition rate versus the pumping power are shown in figure 6. When the second concentration (0.5 wt% MWCNTs' SA) was inserted inside the cavity, the Q-switching operation was initiated at pump power of 40 mW, the obtained pulse width was 10.4 µs and the PRR was 3.5 KHz at pumping threshold as it is presented in figure 7. the output laser was stable centered at 1566.3 nm as it is shown in figure 8. The average output power and the pulse energy as a function of the pump power are illustrated in figure 9. The pulse width and the pulse repetition rate versus the pumping power are presented in figure 10.

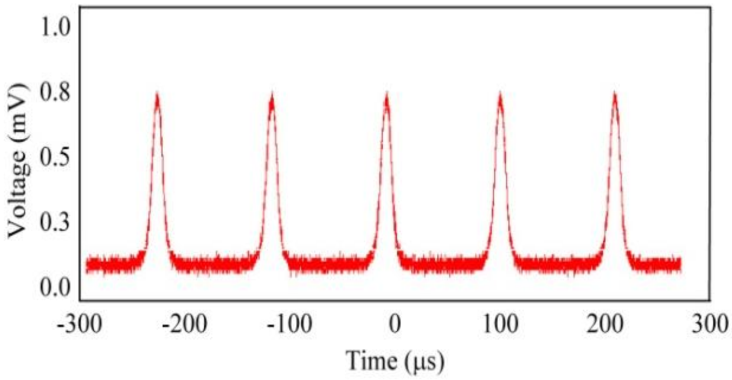


**Figure (3**) Optical pulse train of 0.25 wt% MWCNTs SA at pumping threshold of 25 mW.

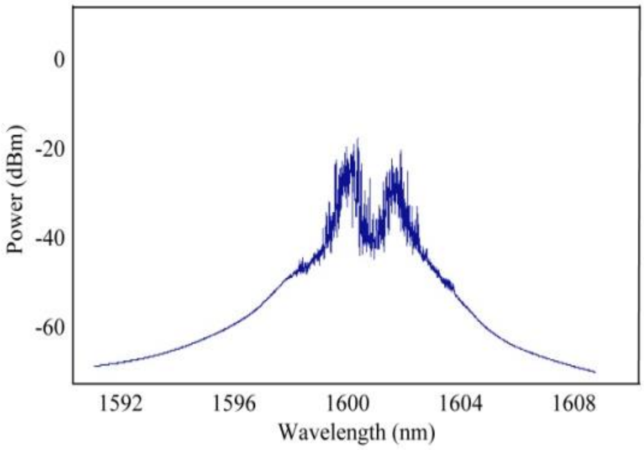


**Figure (4)** Measured optical spectrum of Q-switched EDFL with 0.25 wt% MWCNTs at pump power of 143 mW.

The insertion of 0.75 wt% MWCNT's SA allowed the Q-switching operation to start at 40 mW and the corresponding pulse width and the PRR were 14 μs and 15.6 KHz, respectively as it is illustrated in figure 11. The optical spectrum of the output laser showed high stability at 1566.2 nm as it is shown in figure 12. The average output power and the pulse energy as a function of the pump power are illustrated in figure 13. Figure 14 shows the pulse width and the PRR versus the pumping power.

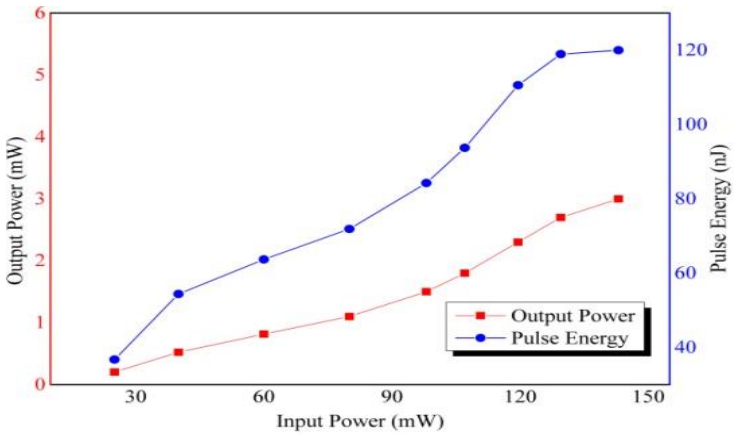


**Figure (5**) The output power and pulse energy versus the pump power in case 0.25 wt% MWCNTs SA.

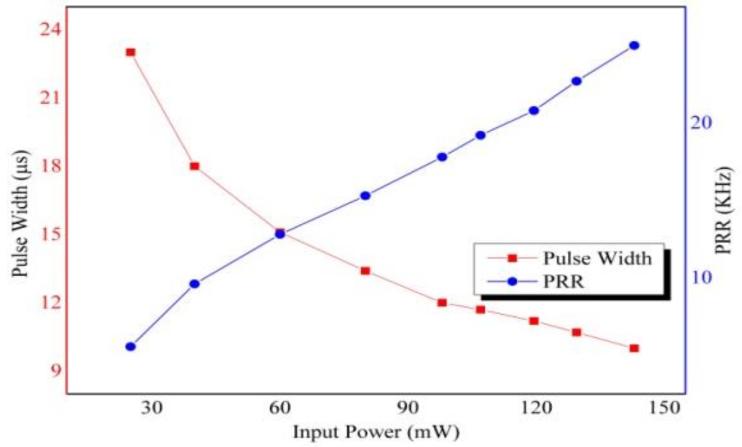


**Figure (6)** Pulse width and pulse repetition rate of the proposed Q-switched EDFL in case of 0.25 wt% MWCNTs SA.

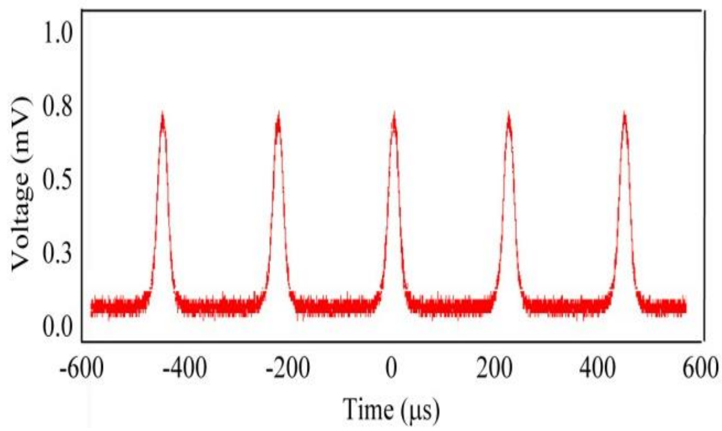


**Figure (7)** Optical pulse train of 0.5 wt% MWCNTs SA at pumping threshold of 40 mW.

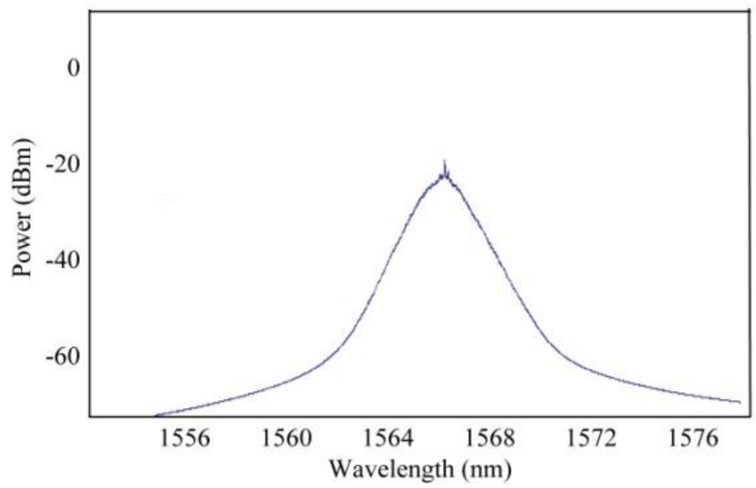


**Figure (8)** Measured optical spectrum of Q-switched EDFL with 0.5 wt% MWCNTs at pump power of 218 mW.

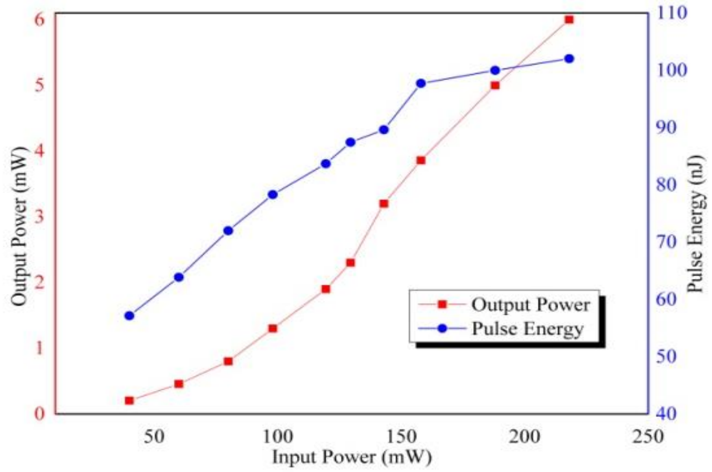


**Figure (9)** The output power and pulse energy versus the pump power in case 0.5 wt% MWCNTs SA.

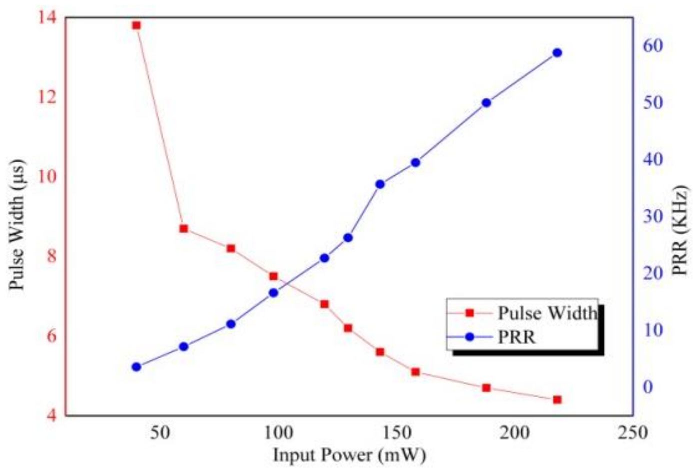


**Figure (10)** Pulse width and pulse repetition rate of the proposed Q-switched EDFL in case of 0.5 wt% MWCNTs SA.

The modulation depth and nonsaturable losses are clearly sensitive to the concentration of MWCNTs SA. The modulation depth increased as the MWCNTs occupied by the sample concentration increased, the modulation depth is expected to be lower and the saturation intensity is higher than those recorded by reference [16]. So, that better pulse shaping is obtained with the SA of higher MWCNTs concentration.

When the pump power increases, more gain is achieved to saturate the SA, thus the pulse repetition rate for each concentration was largely increased with the pump power. It can be noticed that the PRRs for the three SAs were function of the pump power unlike the mode-locking case, in which the PRR is cavity length dependent and that verify the Q-switching operation. For the 0.25 wt% concentration SA, the measured pulse width was gradually decreased from 23 µs at 25 mW threshold pump power up to minimum pulse width of 11.2 µs at a pump power of 119 mW. The average output power continued increasing as a function of pump power but no Q-switched pulses were observed when the pump power increased more than 119 mW. In case of 0.5 wt% concentration SA, the measured pulse width was shortened from 10.4

μs at 40 mW pump power to minimum pulse width of 4.4 μs at a pump power of 218 mW after which, no more pulses were appeared. While for 0.75 wt% concentration SA, the pulse width was decreased from 14 μs at threshold pump power of 40 mW down to 4 μs at 300 mW pumping power.

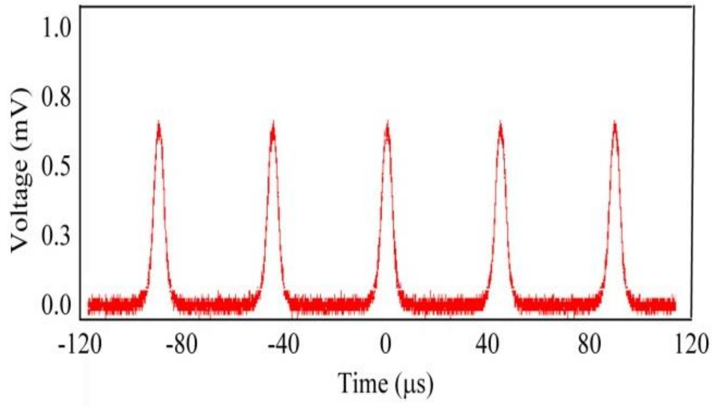


**Figure (11)** Optical pulse train of 0.75 wt% MWCNTs SA at pumping threshold of 40 mW.

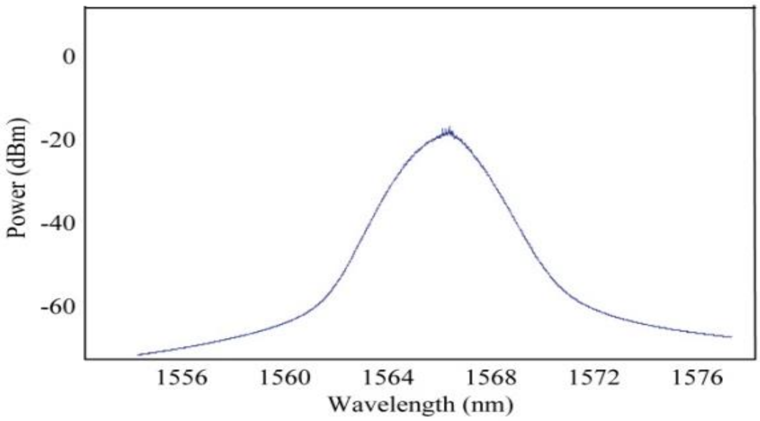


**Figure (12)** Measured optical spectrum of Q-switched EDFL with 0.75 wt% MWCNTs SA at pump power of 300 mW.

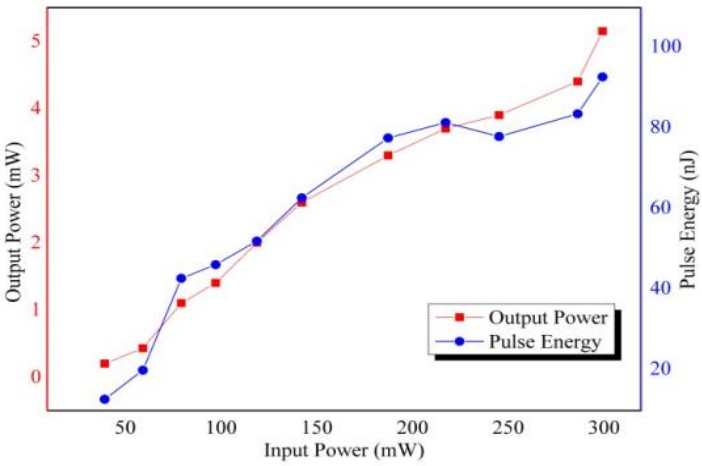


**Figure (13)** The output power and pulse energy versus the pump power in case 0.75 wt% MWCNTs SA.

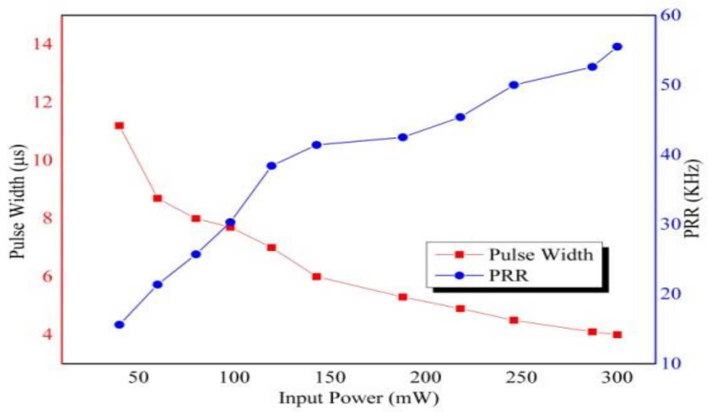


**Figure (14)** Pulse width and pulse repetition rate of the proposed Q-switched EDFL in case of 0.75 wt% MWCNTs SA.

## 5. Conclusions

We experimentally investigated the effect of MWCNTs concentration in MWCNTs dispersed in PVA polymer matrix on stability and pulse width of passively Q-switched EDFL. The SA of higher concentration (0.75% MWCNTs) showed very stable output at 1566.2 nm, shortest pulse width of 4 µs and higher PRR tuning rang with pump compared with the other investigated lower concentrations. However, decreasing the concentration of MWCNTs to 0.25 wt% led to unstable laser output, wider pulse width of 11.2 µs and narrower pulse width and PRR tuning range as a function of pumping power.

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