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# Passively Q-Switched Erbium-Doped Fiber Laser with Tris (8-hydroxyquinolinato) Aluminium ($Alq_3$) Film Saturable Absorber

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**ABSTRACT**

This paper experimentally demonstrates Q-switched Erbium-doped fiber laser (EDFL) by using organic semiconductor material Tris (8-hydroxyquinolinato) aluminium ($Alq_3$) in the form of thin film as a saturable absorber (SA). The fabricated $Alq_3$ thin film is cut into small pieces and incorporated between two ferrules in EDFL cavity, a stable and compact Q-switching pulse train was achieved. As the 980 nm pump power was increased from 45 mW to 98 mW, the repetition rate of the EDFL increased from 70.42 kHz to 91.24 kHz while the pulse width became narrower from 4.48 µs to 3.26 µs. The maximum pulse energy and peak power is 73.214 nJ and 22.458 mW is generated with repetition rate and pulse width of 70.42 kHz and 3.26 µs, respectively. The findings suggest that the proposed $Alq_3$ material is viable as a saturable absorber (SA) in achieving a consistently stable and adaptable Q-switched laser for operation at 1.5 µm wavelength.

## 1. Introduction

Erbium-doped fiber lasers (EDFLs) is operated at 1.55 µm region have a broad attracted for these last few years due to their low cost, flexibility [1], and simplicity of design [2], and bring up a variety application in material processing (industrial and laser) [1,3], optical communication, micromachining [4], spectroscopy [5], and so on. Usually, Q-switched can be classified into an active or passive approach based on the use of active modulation of the Q-factor in the cavity [6]. For the active Q-

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switching, when the electron-optic or acoustic-optic modulator is inserted into the laser cavity, the difficult operation in the laser cavity happens. In other cases, for passive Q-switching, when the saturable absorber is inserted into the cavity, which acts as a Q-switcher. For the active Q-switching, it has advantages such as repetition rate control by the pump power and timing synchronization, it also has disadvantages such as damage at lower threshold, low peak power and high-cost [7].

Recent years, different excellent types of saturable absorber were introduced to obtain the passively Q-switched pulse laser such as semiconductor saturable absorber mirrors (SESAMs) [8], graphene [9-11], carbon nanotubes (CNTs) [12,13], topological insulators [1], transition metal oxide (TMO) [14] and others have been reported as saturable absorbers. The use of semiconductor saturable absorber mirrors (SESAMs) as a saturable absorber has limitations in terms of narrow operation range bandwidth, the packaging is high cost and the fabrication is complicated [1]. Graphene is one of the materials included in the 2D materials, graphene has been characterized as one of the ideal SA because it has zero-bandgap which offers some benefits such as broadband and fast saturable absorption and ultra-fast recovery time [15]. Besides that, it also has drawbacks such as suffering intrinsic limitations of weak absorption in a low modulation depth [16]. Other than graphene, CNT is also one of the 2D materials, CNT were the choice for SAs due to their optical fiber compatibility, low saturation intensity, wide operating bandwidth, not highly cost, and fabrication is simple [17]. However, the complex bandgap control, which limits saturable absorption from happening at a certain wavelength [18]. Because the drawbacks of graphene and CNT, research has also identified the interest to topological insulators (Tis) as a SA such as bismuth selenide ($Bi_2Se_3$) and bismuth telluride ($Bi_2Te_3$), which are from the Tis group, and have gapless in the bulky state that can cause the complex construction process and so that the applications become limited [19].

For a few years, the research has been carried out in order to find new materials to behave as a saturable absorber that is able to generate the pulse in the 1.0 µm up to 2.0 µm region. Recently, there has been new interest in organic materials such as Tris (8-hydroxyquinolinato) aluminium ($Alq_3$). Organic materials are matter that has come from a recently living organism. $Alq_3$ is one of the organic materials that able endurance at high photoconductivity, and its operational lifetime is long [20], good in terms of heat resistance, and high stability thin film formation [21]. Other than that, organic materials also have tremendous optical properties such as having a broad spectral tunability and ultrafast nonlinear response. Organic material is important in a few applications such as light-emitting diodes (OLEDs) [22], solar cells [23], bi-stable memory devices [24] and organic thin film transistor [25]. As compared to the other materials, organic materials are not dangerous and have no long-term exposure for human health.

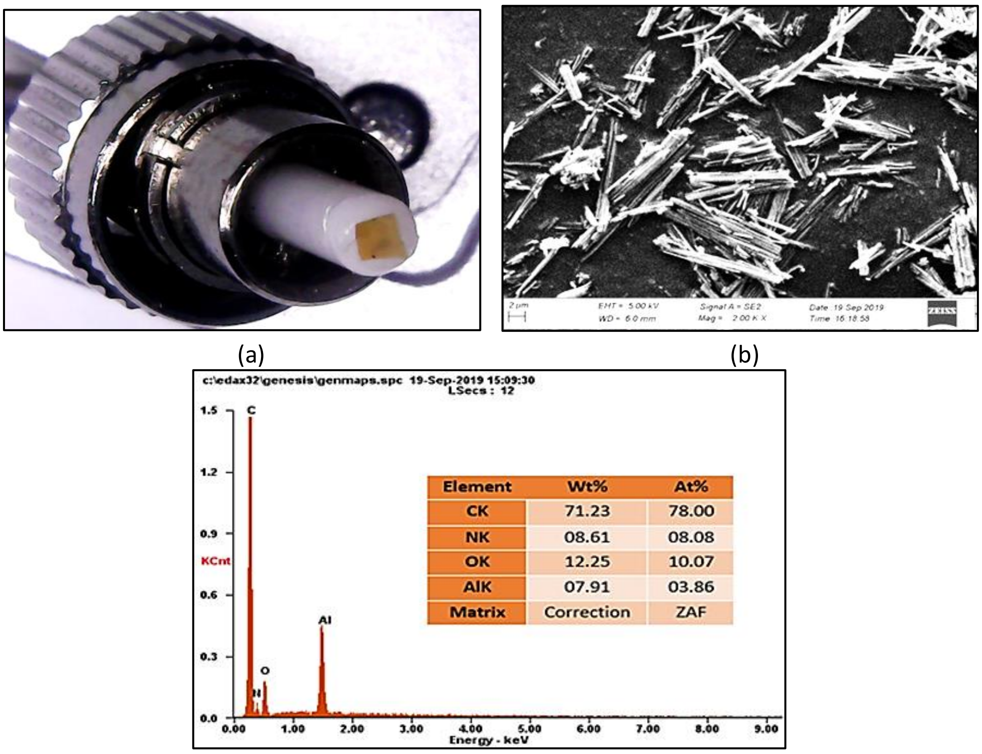
In this paper, a passively Q-switched fiber laser is developed using Tris (8-hydroxyquinolinato) aluminium ($Alq_3$) organic semiconductor as a saturable absorber using an Erbium doped fiber as a gain medium. $Alq_3$ has a bandgap energy of about 2.7 eV [19] and it provides great advantages such as inexpensive cost of production, mechanical flexibility and light-weight. For this purpose, we prepare $Alq_3$ in the form of thin film. The film is used in a fully fiber-integrated laser cavity for generating a stable Q-switching. By incorporating a small piece of the film in a laser cavity, the proposed laser generates a stable Q-switched pulse train at 1560 nm with repetition rate increases from 70.42 kHz to 91.24 kHz while the pulse width decreases from 4.48 µs to 3.26 µs as the pump power is increased from 45 mW up to 98 mW. In the following subchapters, we briefly describe the process of fabricating SA film, optical characterization of SAs, laser configuration, laser operation for Q-switched, and conclude with a summary of the invention.

## 2. Methodology

### *2.1 EDFL Characterization of SAs*

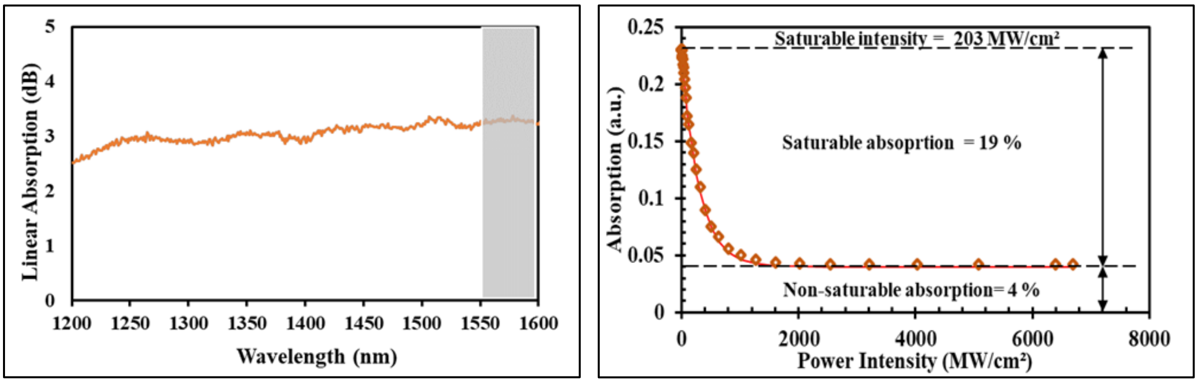
In this experiment, we used $Alq_3$ in the form of powder to fabricate as a SA and proposed this $Alq_3$ SA film to generate the Q-switched pulsed laser. The organic compound of $Alq_3$ was purchased from Sigma Aldrich. At first, 10 mg of the $Alq_3$ powder was stirred with 1 ml of the distilled water. The stirring process takes one hour at the temperature of 50˚C. After that two drops of acetone were dropped into the solution to make sure that the equal distribution of $Alq_3$ inside the solution. Other than that, the PVA solution was prepared with 1 g of PVA, was added in 100 ml distilled water and then followed by the ultra-sonication for about one hour at room temperature. Next step, 5 ml of PVA was mixed with the $Alq_3$ solution. The mixture was stirred for about three hours at room temperature by using a magnetic hot plate stirrer. After three hours, the mixture was poured into a glass petri dish and left to dry at room temperature for nearly three days to form a film with thickness of 50 µm and it easily peeled from the petri dish. Lastly, the $Alq_3$ PVA film was cut into a small piece and sandwiched between two fiber connectors via a fiber adapter to form a fiber-compatible SA.

Figure 1(a) shows $Alq_3$ thin film on the fiber ferrule. The thin film is in yellow colour. Figure 1(b) depicts the field emission scanning electron microscopy (FESEM) of the $Alq_3$ film and Figure 1(c) shows the energy dispersive spectroscopy (EDS) of the film SA with contain 71.23 % of Carbon, 12.25 % of Oxygen, 8.61 % of Nitrogen, and 7.91 % of Aluminium element. Figure 2(a) shows the linear absorption profile (LAP) of the $Alq_3$ which absorbs around ~3.0 dB at the laser operating region. Figure 2(b) shows the modulation depth (Δα), saturable intensity (Isat) and non-saturable absorption ($\alpha ns$) of the film as 19 %, 203 MW/cm$^2$ and 4 %, respectively.




(c)

**Fig. 1.** (a) $Alq_3$ thin film on the ferrule (b) FESEM image (c) EDS profile




(a) (b)

**Fig. 2.** (a) $Alq_3$ thin film linear absorption profile (b) $Alq_3$ thin film nonlinear absorption profile

## *2.2 EDFL Configuration*

The schematic diagram of the Q-switched EDFL based on $Alq_3$ thin film as a saturable absorber is illustrated in Figure 3. In this work, the EDFL cavity consists of 2.4 m long Erbium-doped fiber (EDF) used as a gain medium. It was pumped by a 974 nm laser diode (LD) via a 980/1550-nm fused wavelength division multiplexer (WDM). The EDF has a cut-off wavelength of 900 nm, numerical aperture of 0.24 and 23.9 dB/m absorption at 980 nm. It has a core and cladding diameters of 5.1 and 125.4 µm, respectively and the peak absorption of 41.1 dB/m at 1530nm. The $Alq_3$ thin film is cut into small pieces (1 mm x 1 mm) and incorporated between two optical fiber connectors via a fiber adapter to form a SA device, which is then integrated into the laser cavity for the Q-switching pulsed laser. A little amount of index matching gel was applied between the ferrules to reduce the parasitic reflections. An isolator was added inside the ring cavity to ensure the light go through in unidirectional propagation. The 90/10 output coupler was spliced into the cavity after the isolator. The 90 % output port is oscillating light in the cavity and the other 10% output port is further divided by 50/50 fiber coupler to enable two simultaneous measurements. An Optical Spectrum Analyzer (OSA: Anritsu, MS9710C, 0.6-1.75 µm) and an oscilloscope (GWINSTEK: GDS-3352) with high-speed photodetector are used to monitor the output spectrum and the pulse trains. 7.8 GHz Radio Frequency (RF) spectrum analyzer (Anritsu MS2683A) is used to analyze and measure the RF spectrum. The average output power of the pulse laser is measured by the power meter (Thorlabs PM 100D) coupled.

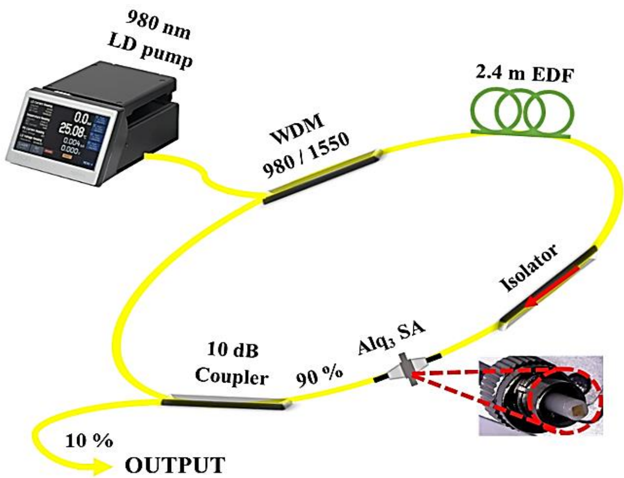



**Fig. 3.** The experimental of the Q-switched fiber laser $Alq_3$ thin film as a SA

## 3. Results

### *3.1 Q-switching Operation*

Passive Q-switching of the EDFL cavity was firstly investigated. The lasing threshold (before inserting the SA) of the laser was obtained at 35 mW while after incorporation of the $Alq_3$ SA into the cavity, a self-starting of the Q-switched EDFL operation was achieved at 45 mW of the pump power. The pulse train of the Q-switched EDFL operation was stable with the increase of pump power up to 98 mW. However, *Q*-switching became unstable and noisy as the pump power was further increased. At even higher pump power beyond 98 mW laser pulsing could no longer be maintained. When the pump power was subsequently reduced to below 98 mW *Q*-switching would again self-start and could be maintained for hours without any evidence of damage to the SA device. Figures 4(a), 4(b) and 4(c) show the Q-switched oscilloscope traces at three different incident pump powers of 45 mW, 72 mW, and 98 mW, which indicates pulse periods of 14.20 µs, 12.24 µs and 10.96 µs, respectively. It indicates that the repetition rate increases while the pulse width reduces with the raise of pump power. This phenomenon is a common feature of passive Q-switching operation.

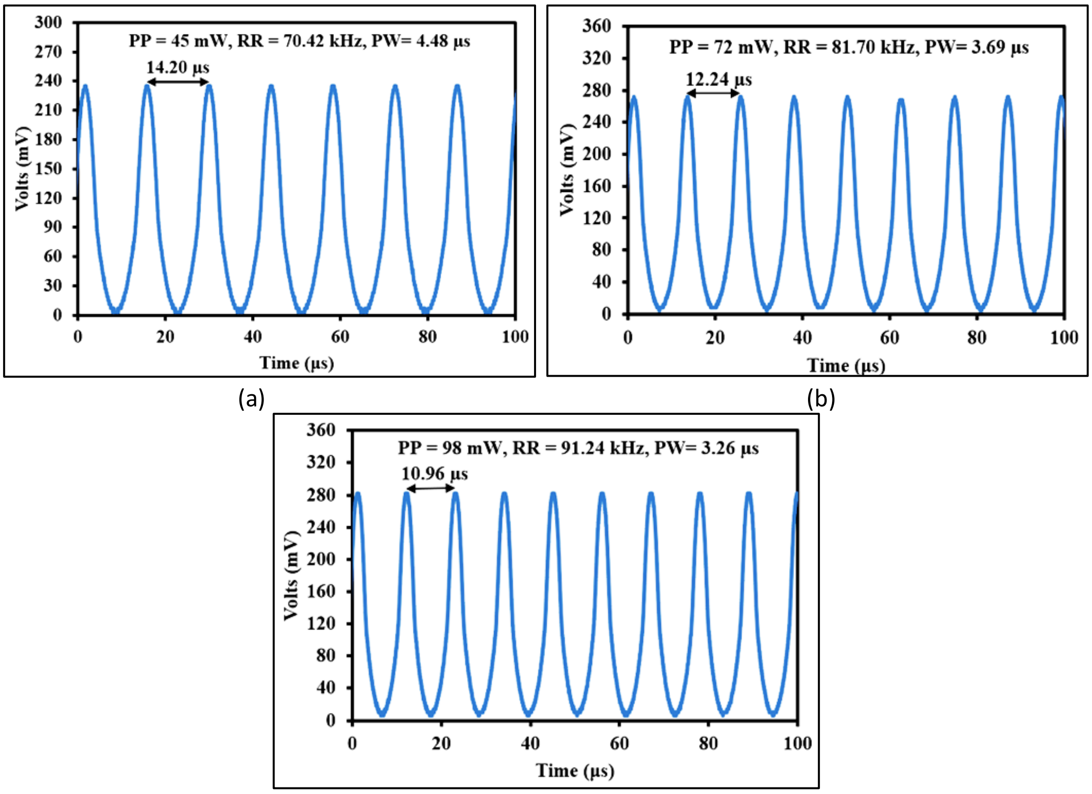



**Fig. 4.** Q-switched oscilloscope traces at different incident pump powers (a) PP = 45 mW (b) PP = 72 mW (c) PP = 98 mW

Figure 5 shows Q-switching performances. The optical spectrum of the Q-switched pulse at 98 mW pump power, as shown in Figure 5(a). It has a central wavelength at 1560 nm with 3 dB bandwidth of 2.2 nm, which located in the range of conventional band (C-band) region. Figure 5(b) shows the repetition rates and pulse widths versus different pump powers. As is shown, the pulse repetition rate increased linearly whereas the pulse width reduces with increasing pump power. The repetition rate is 70.42 kHz at the self-start threshold (45 mW), rising to 91.24 kHz at maximum pump power. Meanwhile, the pulse width reduces from 4.48 µs to 3.26 µs, which are typical features of passively Q-switched fiber lasers. The corresponding pulse energies and average output powers under different pump power were shown in Figure 5(c), as is shown, the pulse energy and peak power all increased with the growth of the pump power. The output power was increased from 2.48 mW to 6.68 mW with a slope efficiency of 7.98 % as the pump power increased from 45 to 98 mW. The pulse energy also linearly increased from 35.217 nJ to 73.214 nJ as the pump power was increased within the same range.

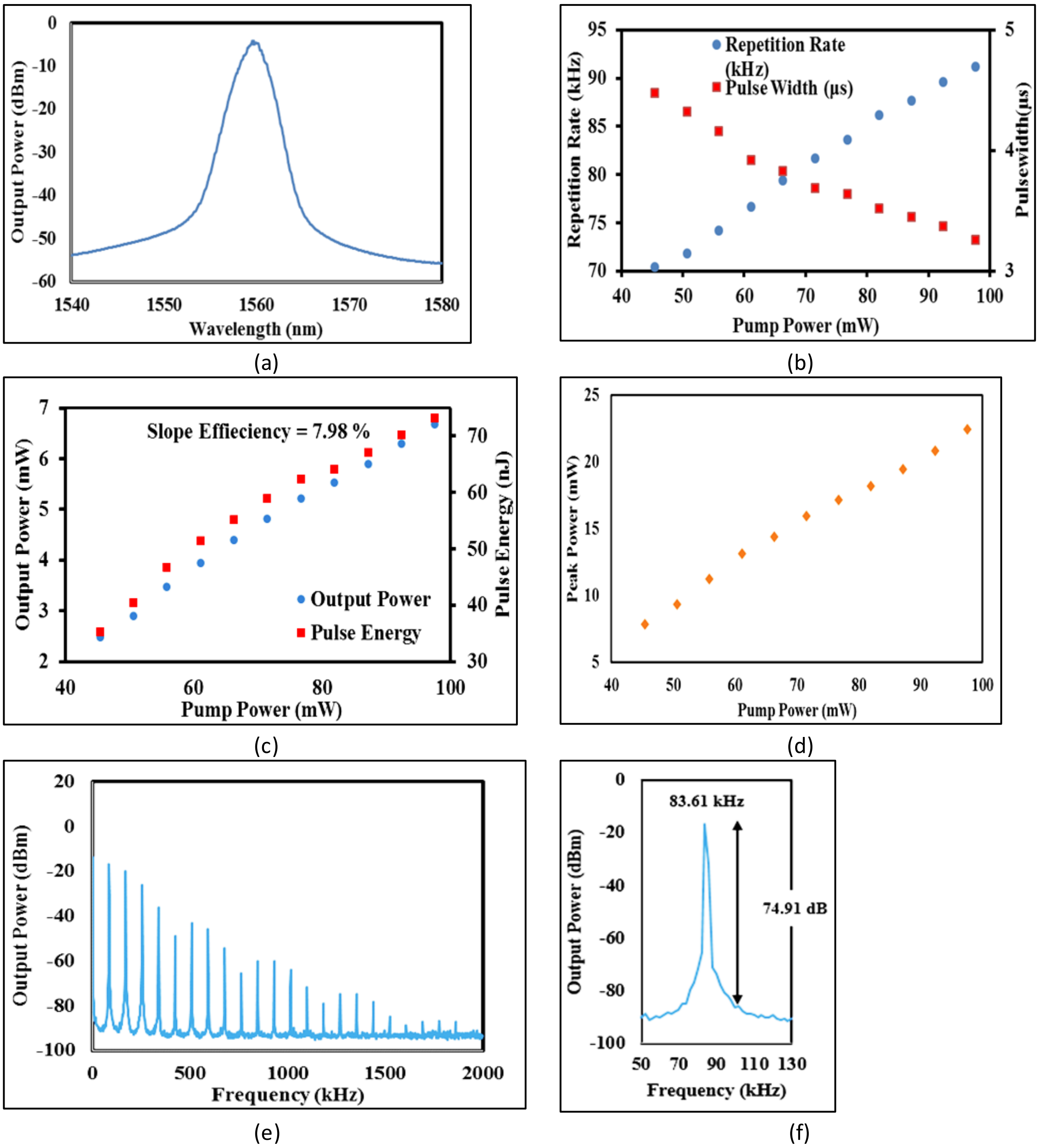



**Fig. 5.** Q-switching performances (a) Output spectrum of the $Alq_3$ based Q-switched EDFL (b) Pulse repetition rate and pulse width as functions of pump power (c) Average output power and pulse energy as functions of pump power (d) The relationships between the peak power and pump power (e) Radio-frequency (RF) spectrum at input pump power 77 mW with a span of 2000 kHz (f) With a span of 80 kHz

Subsequently, the relationships between the peak power and the pump power are shown in Figure 5(d). It is obvious that there is a clear linear relationship between the pump power and the peak power. The peak power of 22.458 mW was obtained at maximum pump power of 98 mW. The stability of the $Alq_3$ based passively Q-switched fiber laser under the input pump power of 77 mW was tested by a RF spectrum analyzer. Figure 5(e) depicts the RF spectrum within a wide span of 2000 kHz. It shows more than 22 harmonics with the fundamental repetition rate was located at 83.95 kHz. In addition, the fundamental repetition rate was shown in Figure 5(f) with a span of 80 kHz. The signal-to-noise ratio (SNR) of the frequency was obtained at 74.91 dB. The results of the RF spectrum all prove that $Alq_3$ based passively Q-switched fiber laser with high stability was obtained in this work.

## 4. Conclusions

A stable and simple Q-switched EDFL is successfully demonstrated using organic semiconductor material $Alq_3$-SA. The Q-switched pulse laser was achieved to operate at 1560 nm region. As the 980 nm pump power was increased from 45 mW to 98 mW, the repetition rate of the EDFL increased from 70.42 kHz to 91.24 kHz while the pulse width became narrower from 4.48 µs to 3.26 µs. The basic frequency of the EDFL Q-switched has signal-to-noise ratio (SNR) was about 74.91 dB. The maximum pulse energy and peak power is 73.214 nJ and 22.458 mW is generated with repetition rate and pulse width of 70.42 kHz and 3.26 µs, respectively. As compared to the other material, the $Alq_3$ organic semiconductor material has a great performance which is consistently stable and adaptable, offering significant potential in diverse photonics applications such as optical communication and micromachining.

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