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Controlling the Occurrence of Rogue Waves in an Optically Injected Semiconductor Laser via Changing The Injection Strength

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Abstract: The rouge waves in an optically injected semiconductor lasers are receiving a lot of interest. In this work, the generating and controlling of the rogue waves in semiconductor lasers have been investigated. For this purpose, the laser's rate equations are solved numerically in a specified time interval, then the field amplitude and the intensity versus time are calculated and analyzed. To solve the rate equations, the famous finite deference method (FDM) is used. Also the rouge waves are counted using the standard definition that is mentioned in the context. Furthermore, the effects of the injection strength and the detuning frequency on the rogue wave's occurrence are studied. Results show that by increasing the injection amplitude, the number of rogue waves decreases significantly, so that rouge waves vanish at the large values of the injection amplitude. Also increasing the detuning frequency, reduces the number of rogue waves and this reduction is more sensitive at the large injection amplitude.

Key words: Rogue waves, semiconductor lasers, detuning frequency.

1. INTRODUCTION

Rogue waves (RWs) were first used to talk about extreme and rare events that unexpectedly occur in the ocean even in relatively calm situations [1, 2]. Researchers offered several definitions for these waves which the most important of them are as follows: they have a large amplitude (twice or more than of the average height of waves), they are unpredictable and belong to the tail of the L-shaped probability density function [3, 4]. Ocean rogue waves that

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also called freak waves are like wall of water that appear suddenly, rise fast, fall fast and disappear in the blink of an eye. However, it happens quickly but has extraordinary power that is very destructive and causes a lot of damage like boat accidents, taking the lives of people and etc. [1, 5]. The term rogue wave is not limited to oceanographic and used in other field of science ranging from fluid dynamics and matter physics to plasma physics and nonlinear optics [4-7]. The major challenge is to find the physical mechanism that generate them, to figure out how they develop, to calculate the incident probability and generally to find ways controlling them, so that making safer environments and systems.

The science of rogue waves has brought to optics for the first time in 2007 when Solli group analyzed supercotinuum generation in optical fibers and observed high amplitude intensity pulses at the certain wavelengths in the chaotic spectrum from supercontinuum [5]. They also showed that the broad band output can be generated from a narrowband input exactly like rogue waves in the ocean [6,8]. Since then, we can see that rogue waves have been seen in many optical systems such as erbium doped fiber systems, Raman fiber amplifiers, vertical cavity surface emitting lasers, mod locked lasers and etc. [5-8].

From rogue waves characteristics that already mentioned, it could be understood that the system which exhibits these rare and extreme events must be nonlinear so the dynamics of rogue waves should be study by solving the nonlinear Schrodinger equation (NLSE) [5,9].

Numerous studies have been done in this area in which the most recent and important one is belong to Zamora et. al. They have been investigated the effects of the noise and the current modulation on the occurrence of rogue waves in semiconductor lasers to control the RWs occurrences [6, 8]. The control of the RWs and specially vanishing them could be widely applicable in lasers and fiber optics. [5, 6, 8]. Since in nonlinear systems RWs can be suppressed by weak noise and direct current modulation of a control parameter [6, 8], the main part of this work is investigating the effects of injection strength and detuning frequency on rogue waves by solving laser rate equations and finding if rogue waves can be also controlled by injection strength and detuning frequency variations. with these purpose the producing of RWs in an optically injected semiconductor laser by changing the injection strength and detuning frequency is studied. Here we use the rate equation model that is previously studied in [6, 8] to investigate the effects of injection on rogue waves for different detuning frequencies.

2. THEORY

Induced dynamics in a single mode semiconductor laser could be modeled by the following two rate equations [6, 8, 9]:

$$\frac{dE}{dt} = \kappa(1+i\alpha)(N-1)E + i\Delta\omega E + \sqrt{P_{inj}} + \sqrt{D}\xi,$$

$$\frac{dN}{dt} = \gamma_N\left[\mu - N - N|E|^2\right].$$

Where E and N are the slowly varying complex amplitude and the carrier density of the slave laser and also P_{inj} is the optical injection strength, $\Delta\omega = \omega_s - \omega_0$ is the detuning between the master and the slave lasers, i is imaginary unit and ξ is a complex Gaussian white noise representing spontaneous emission. The fixed parameters are: the field decay rate, κ=300ns^{-1}, the carrier decay rate, γ_N=1ns^{-1}, the line-width enhancement factor, α=3, the injection current, μ=2.2 and the noise strength, D=0.0001 [8].

The important point here is defining a threshold value that is a function of the mean value of intensity and its standard deviation. Here we defined it as $\tau = \langle I \rangle + 2\sigma$, and a wave which its intensity is more than this value is considered as the rogue wave.

3. RESULTS AND DISCUSSION

Intensity versus time for different values of injection and detuning is plotted in Fig. 1. In this figure the threshold value is shown by a red line and the pulses which are above this red line are counted as the rogue waves. It is observed that in all the figures the averages of intensities are almost the same and the intensity fluctuations occur around this specified value. It should be mentioned that the behavior of rogue waves with respect to injection strength and detuning frequency is investigated later but here the output of the considered laser for special values of injection strength is depicted. The values for detuning frequency are $\Delta\nu_0$, $2\Delta\nu_0$ and $4\Delta\nu_0$ that appropriately shows the effect of detuning frequency and for the injection two different values (small and large values) is selected. The parameters were chosen so that the different laser outputs were clear. The Fig. 1 is revealed the laser signal with high, average and low rogue wave.

Fig. 1(a) and (b) are plotted for detuning frequency of $\Delta\upsilon = 0.5\text{GHz}$ and $P_{inj} = 60ns^{-2}$ and $P_{inj} = 320ns^{-2}$ respectively. In Fig.1 (a) the average intensity is about 1.40 and the threshold value is 3.70. It is obvious that the number of detected rogue waves decreases by increasing the injection strength (in following rogue waves versus injection strength is depicted). Fig. 1(c) and (d) respectively show intensity versus time for $P_{inj} = 60ns^{-2}$, $P_{inj} = 320ns^{-2}$ and $\Delta\upsilon = 1\text{GHz}$ for both of them. Here also by increasing the injection strength (60 ns^{-2} to 320 ns^{-2}) the number of rogue waves decreases significantly. As it is obvious form Fig. 1(d) no rogue waves are detected. Finally, Fig 1. (e) & (f) with $P_{inj} = 60ns^{-2}$, $P_{inj} = 320ns^{-2}$ and $\Delta\upsilon = 2\text{GHz}$ are presented at the end of the Fig.1. These two figures also illustrate that by increasing the injection strength at the fixed detuning frequency, the number of rogue waves reduces. The average intensity for all parts in Fig.1 is around 1.4-1.7. Trend of them are almost the same except Fig 1. (e). In this figure threshold value is less than the others and so that the heights of occurred rogue waves have reduced rather than other figures.

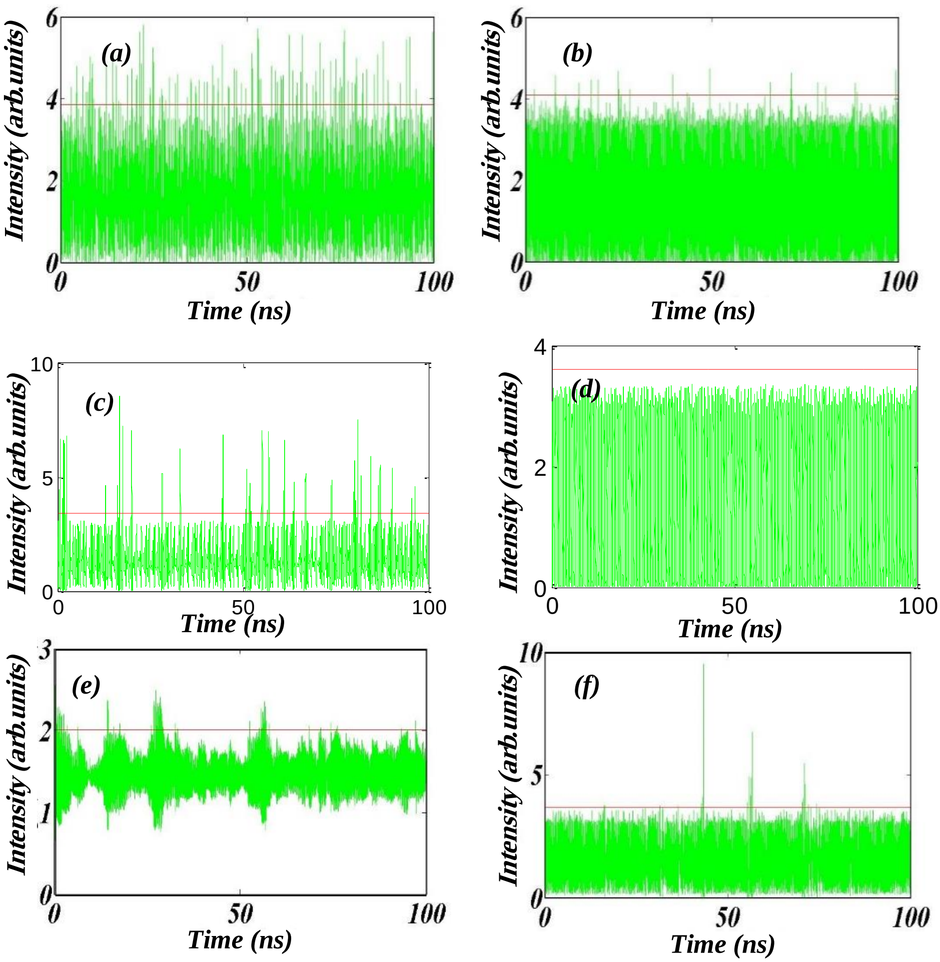

Fig.1: Intensity versus time (a): $P_{inj} = 60ns^{-2}$ and $\Delta\upsilon = 0.5GHz$, (b): $P_{inj} = 320ns^{-2}$ and $\Delta\upsilon = 0.5GHz$, (c): $P_{inj} = 60ns^{-2}$ and $\Delta\upsilon = 1.0GHz$, (d): $P_{inj} = 320ns^{-2}$ and $\Delta\upsilon = 1.0GHz$, (e): $P_{inj} = 60ns^{-2}$ and $\Delta\upsilon = 2.0GHz$ and (f): $P_{inj} = 320ns^{-2}$ with $\Delta\upsilon = 2.0GHz$.

The Fig. 1 is clearly shows the tunability of the rogue wave occurrence by changing the injection strength for different detuning frequencies. The noticeable result is vanishing the rogue waves for very strong injection power that is useful for some laser application. It should be also mentioned that for high detuning frequencies and weak injection the pattern of laser intensity is drastically changed. Furthermore, the average detuning frequency and weak injection could result in huge rouge waves (intensity≈10, it is also rarely observed at high detuning frequency and strong injection).

The number of the RWs versus injection strength (P_{inj}) for three different values of detuning frequencies is depicted in Fig. 2. Fig.2 (a) ($\Delta\upsilon = 0.5GHz$) shows that the increasing injection strength first leads to increasing the rouge waves and by increasing more, the rogue waves decreases and will be vanish completely for higher values of injection strength.

Fig.2 (b) and (c) show the behavior of RWs in term of injection strength for $\Delta\upsilon = 1GHz$ and $\Delta\upsilon = 2GHz$ respectively. In these two figures the trend is descending at all, but as it is obvious, at some points stronger injection causes the increase of the number of rogue waves which is shown as the fluctuations in figures.

By comparing three parts of Fig.2 it is clear that increasing detuning frequency causes a reduction in the number of rogue waves, (except for a few points), although there are some fluctuations that are caused by the noise in the rate equations which increases by increasing the detuning frequency. On the other hand, in these three figures with increasing injection strength, after a specified value, there is no rogue waves and this specified value decreases when detuning frequency increases.

It is it is noteworthy to mention that increased the number of rogue wave don't result in the stronger rouge waves, that is clear in Fig. 1. This figure gives an appropriate picture for controlling the rogue waves in optically injected solid state laser using injection that is comparable to [8] and could be complete the scheme of that work.

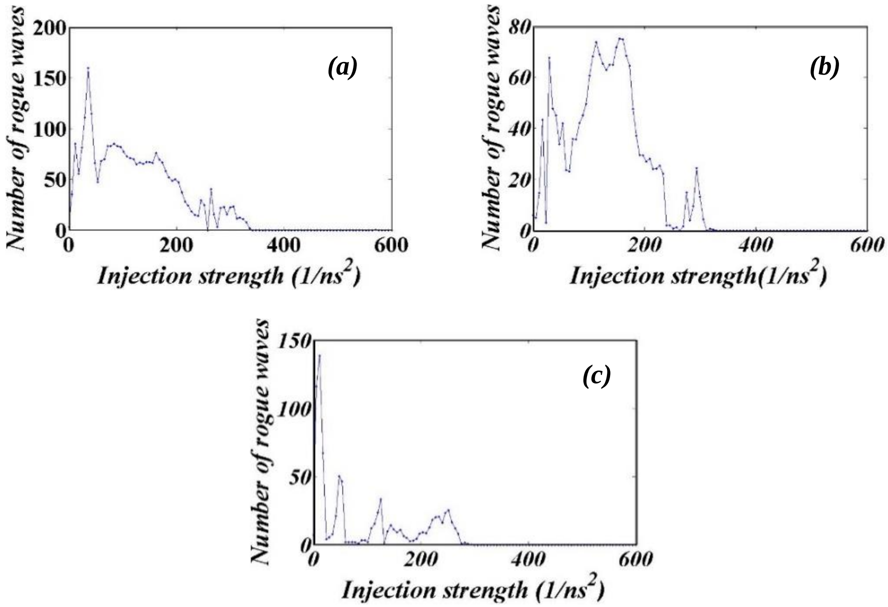

Fig.2: Number of detected RWs versus injection strength P_{inj} for (a) $\Delta\upsilon = 0.5\text{GHz}$, (b) $\Delta\upsilon = 1.0\text{GHz}$ and (c) $\Delta\upsilon = 2.0\text{GHz}$.

4. CONCLUSION

Nowadays, rogue waves are the subject of interest to many researchers. Due to the destructive potential of rogue waves, the major challenge is to suppress these waves. In other words, the focus of the scientists is controlling the rogue waves and reducing damages to the systems.

Here the dynamics of rogue waves in an optically injected semiconductor laser has been studied numerically. The main focus of the present work, was producing and controlling high amplitude pulses, called rogue waves and by changing the values of injection strength and detuning frequency, behavior of the detected rogue waves in this laser type has been investigated. It is observed that at the larger injection strength the rogue waves decreases or even completely suppress. Furthermore, stronger detuning frequency also reduces RWs.

Therefore, by setting the appropriate value of injection strength and detuning frequency we could generate and also suppress the rogue waves and it is possible to control the rogue waves.

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