Hisham K. Hisham
Electrical Engineering Department, Faculty of Engineering, Basra University, Basra, Iraq.
husham_kadhum@yahoo.com

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Controlling the Q-Point in Distributed Feedback Lasers Using a Numerical Optimization Methodology

Abstract*-In this paper, a new methodology for controlling the Q-point in the distributed feedback (DFB) lasers is proposed. The method based on reducing the DFB transient period (T_P) by optimizing laser's model parameters numerically. The analysis has taken into account investigated the effects of the laser injection current (I_{inj}), the dc-bias level (I_{bias}), the temperature (T) variation, and the gain compression factor (ε). Results showed that by optimizing the value of I_{inj}, I_{bias}, T and ε; the Q-point could be controlled effectively. Where increasing the current ratio (i.e., I_{inj}/I_{th}) leads to reduce the T_P value. In addition, by increasing I_{inj} and/or Ibias, the relaxation oscillation period (TRO) and the laser delay time (T_{Delay}) are reduced significantly. From the other hand, the temperature varying may push the DFB laser to operate in an improper region through increasing the TP value; which may lead it to operate in the off-mode. Moreover, as ε is increased, the sinusoidal oscillations are dramatically damped results in a reduction in the TRO value and larger period of stabilized.*

Keywords*- Critical system, Distributed feedback (DFB) lasers, dynamic characteristics, Equilibrium (Q-point) point, semiconductor diode lasers (SDLs) transient response.*

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1. Introduction

Despite the many laser's types, the competitive advantages of distributed feedback (DFB) laser as the small size, low power consumption and their ability to perform direct modulation at high bit rates up to 10 Gb/s make it widely used in most lightwave systems [1,2]. In addition, the high growth in users of optical systems is required a high-speed data transmission [3]. Having the ability to perform high-speed modification, semiconductor laser diodes (SLDs) become an excellent choice for wavelength division multiplexing (WDM) systems. However, the effect of the temperature on the laser wavelength represents the main challenge that is facing the closer WDM channels spacing [4]. This point has been overcome with the development of DWDM systems. Therefore, lasers with fast response and high stable SM operation have become an imperative [5].

In SLDs, producing photons occurs when the carrier concentrations (*N*) exceed its threshold value (N_{th}). Thus there is a delay (T_{Delay}) will appear. Thus, the photon concentration (P) will suffer oscillations before it stabilizes [6,7]. Add to that; the laser is forced to delay due to the threshold condition, therefore there is a time is taken before it reaches to its steady state. This delay possibly leads to significant errors due to the dominance of spontaneous emission effects, or it probably fails to operate due to the long T_{Delay} and high relaxation oscillation period (TRO) which may drive the laser to operate in an improper Q-point region [7-9].

Generally, during the transient period, laser power is distributed among various modes. So, the SLD whose SM operation exhibits poor side mode suppression ratio (SMSR) [8, 9]. Therefore, for fast lasing operation, the study of the response point (Q-point) controlling is important and indispensable. To our information, several studies have been conducted on the DFB lasers [5,6]. However, there is no study has been reported on how the Q-point can be control based on the transient response for the DFB lasers. Therefore, this study will provide important and useful information, especially regarding laser design.

2. Optimization Methodology

For controlling the Q-point in DFB lasers, we proposed a new methodology (as shown in Fig. 1) based on investigating the effects of I_{inj}, I_{bias}, *T* and *ε* separately in order to get the optimal values. The process begins with the DFB laser model. In the next step, all the expressions that describe the model performance are modified to include the effect of T according to Eq. 4 (given in the next section). By referring to Figure 1, if all

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

the analyzed results are accurate (i.e., if Q-point within the acceptable region), the methodology flow proceeds to the next step. If not, analyzing will be repeated again. Finally, the flow will be completed if the analyzed results are correct.

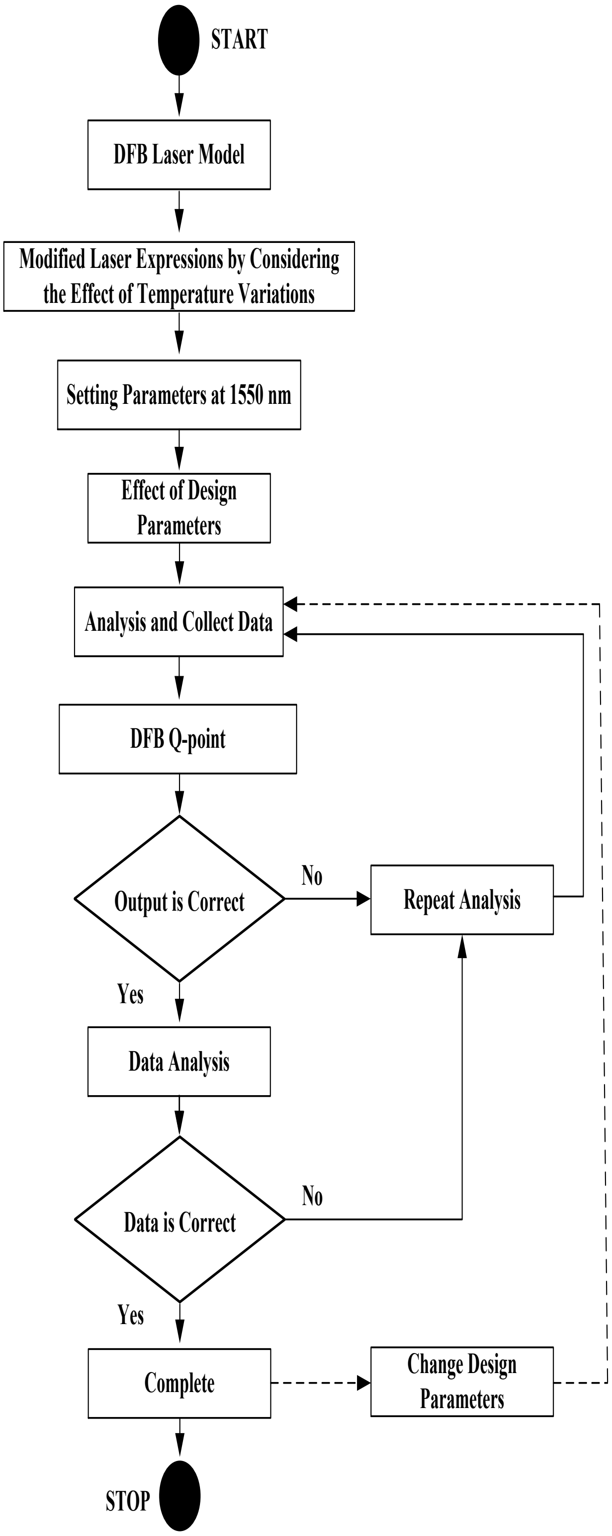

Figure 1: The optimization methodology flow for DFB Q-point controlling

3. Theory

The dynamic characteristics of laser diodes are modeled by coupled rate equations describing the relation between the carrier (N) and photon (P) numbers [8, 9]. The SM rate equations can be described as [5].

$$\frac{dN(T)}{dt}=\frac{I_{inj}}{q}-\frac{N}{\tau_{c,DFB}(T)}-g(T)\frac{N-N_o(T)}{1+\varepsilon(T)P}P \quad (1.a)$$

$$\frac{dP(T)}{dt}=g(T)\frac{N-N_o(T)}{1+\varepsilon(T)P}P-\frac{P}{\tau_{p,OFB}(T)}+\frac{R_{sp,DFB}(T)}{\tau_{c,DFB}(T)}N \quad (1.b)$$

Where q is the electron charge, $\tau_{c,DFB}(T)$ is the temperature depended (TD) carrier lifetime defined by [7, 9]

$$\tau_{c,DFB}(T)=(A+BN(T)+C(T)N^2(T))^{-1} \quad (2)$$

Where A, B and $C(T)$ are the non-radiative, radiative and TD Auger coefficients, respectively, while $\varepsilon(T)$ is the TD gain compression factor, $g(T)$ is the TD gain slope constant and $R_{sp,DFB}(T)$ represents the TD spontaneous emission rate coupled to the lasing mode, given by [7, 9]

$$R_{sp,DFB}(T)=\beta_{sp}\eta_{sp,DFB}(T)(\tau_{c,DFB}(T))^{-1}N(T) \quad (3)$$

Where β_{sp} is the spontaneous emission factor, while $\eta_{sp,DFB}(T)$ and $\tau_{p,DFB}(T)$ are the TD spontaneous quantum efficiency and the TD photon lifetime, respectively [7, 9]. The TD of the model is assumed to vary according to [7]

$$X(T)=X_o+\frac{\partial X}{\partial T}\left(T-T_o\right) \quad (4)$$

Where X_o is the initial value found at the reference temperature (T_o), which is considered at the room temperature (25 ºC).

4. Results and Discussion

One of the most important information can be extracted by solving laser rate equations is the system critical or equilibrium (Q-point) point. Table I shows the typical values of the main parameters that are used in the analysis. In this study, results have been obtained after solving (1) numerically by using MATHCAD software.

Table 1: Parameters used in analysis

Diode Parameters	Description

No = 1×1024 m-3	Transparency carrier density
A = 1×108 sec-1	Coefficient of non-radiative recombination
B = 1×10-16 m3/sec	Coefficient of radiative recombination
C = 3×10-41 m6/sec	Coefficient of Auger recombination
ε = 1×10-17cm3	Gain comparison factor
ao = 2.5×10-20 m2	Differential gain

Figure 2 shows the DFB laser phase plane at a different value of injected current (I_{inj}). As shown, by increasing the value of the I_{inj}, the Q-point has an approximately constant N while P has been changed. Further increasing in the I_{inj} value leads the P value at the Q- point to increase while N remains almost constant. This behavior is due to the dynamic nature for the SLDs above the threshold. Where increasing the number of the photons in the active region leads laser to transition from the unstable (i.e., from the transient) to the stable position (i.e., steady state). This behavior can be seen, as shown in Figure 3.

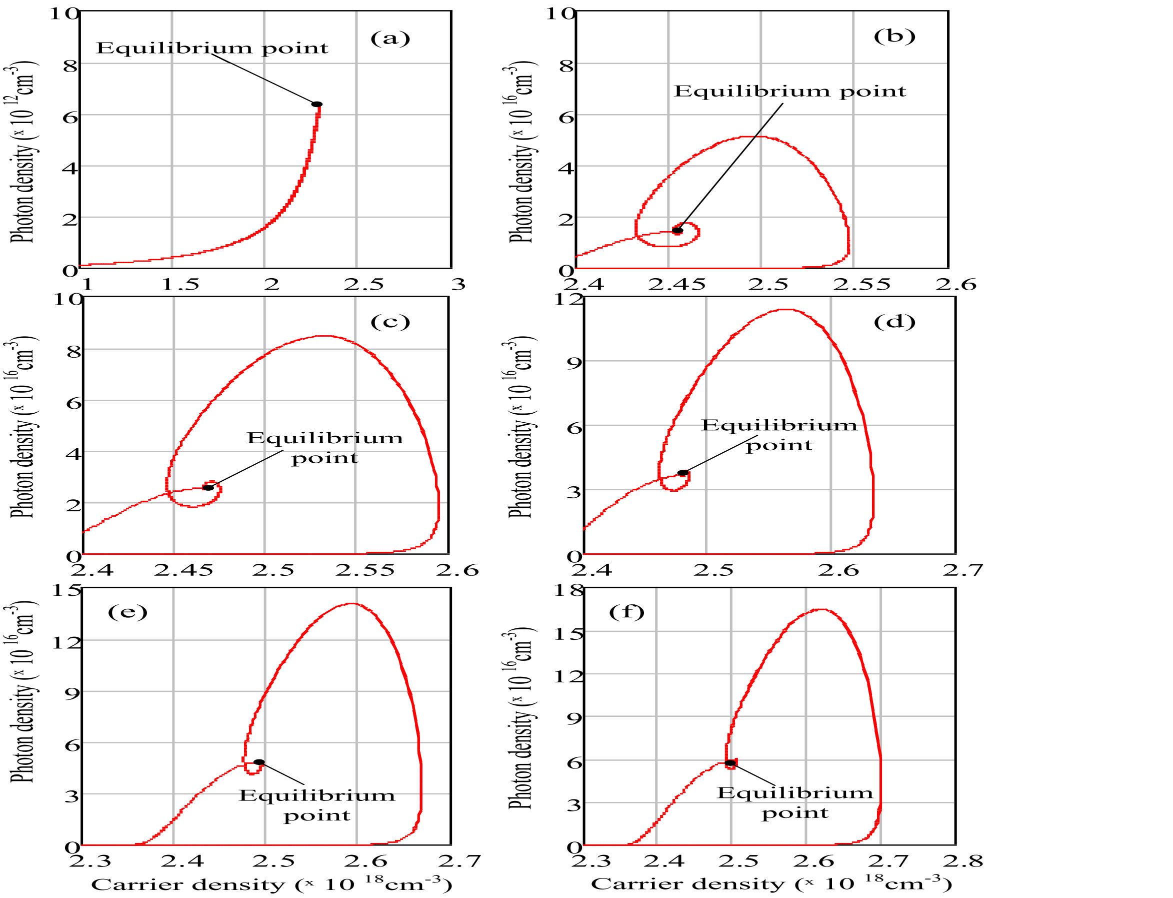

Figure 2: DFB laser phase plane at: (a) I_{inj} = 1 I_{th}, (b) I_{inj} = 2 I_{th}, (c) I_{inj} = 3 I_{th} (d) I_{inj} = 4 I_{th} (e) I_{inj} = 5 I_{th} and (f) I_{inj} = 6 I_{th}

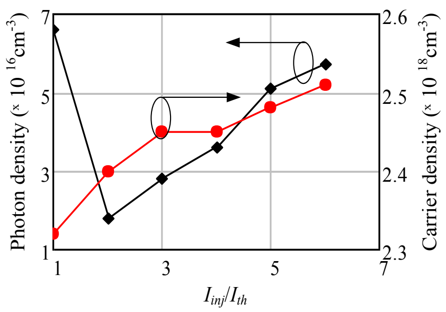

Figure 3: Effect of injected current (I_{inj}/I_{th}) on the DFB photon (P) and carrier (N) densities

Figures 4 and 5 shown the photon (P), the carrier (N) densities during the transient response and the phase plane for DFB laser for several values of I_{inj}= 1.5 I_{th}, 2 I_{th}, 3 $I_{th,}$ and 4 I_{th} at zero bias (i.e., I_{bias} = 0), respectively. The results in Fig. 4 have totally agreed with those being reported in [8,9]. By increasing the laser current to a value above the I_{th}, the P value will not rise for the whole period of the transient (T_{Delay}), and then it gradually increases. During this period, the N and the P populations will oscillate after then attaining their steady-state values. However, by the increase of the I_{inj}, the relaxation oscillation will increase, and in return, the T_{Delay} value will reduce. In addition, by increasing I_{inj} from 1.5 I_{th} to 4 I_{th}, the maximum amplitude for P increases from about 0.1 x 10^{16} cm^{-3} to 1.23 x 10^{16} cm^{-3}, while the TRO decreases from 1.1 to 0.48 ns and the T_{Delay} decreases from about 3.68 to 1.17 ns, respectively. Thus, increasing the I_{inj} leads the Q-point to move from the improper to the stable region as given in Figure 5. Therefore, for fast response and high stable laser, the current ratio (i.e., I_{inj} /I_{th}) should be increasing as large as possible.

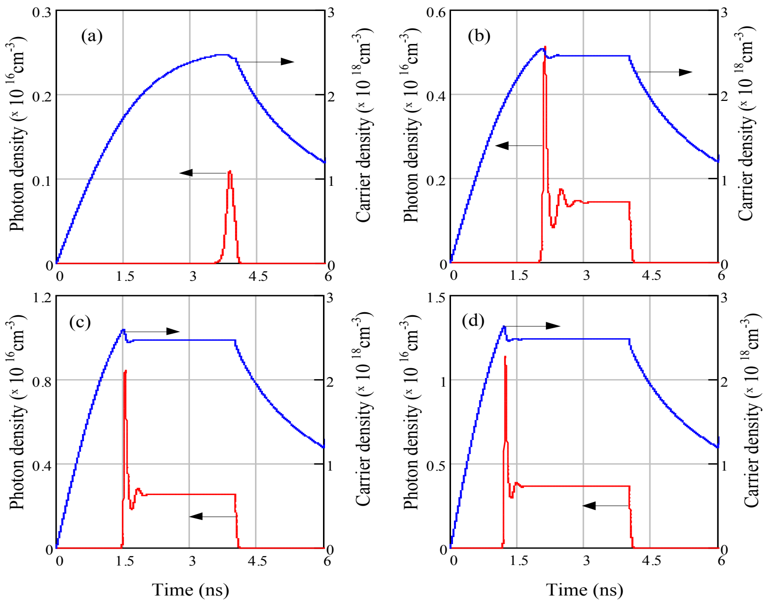

Figure 4: Transient response of DFB laser at: (a) I_{inj} = 1.5 I_{th}, (b) I_{inj} = 2 I_{th}, (c) I_{inj} = 3 I_{th} and (d) I_{inj} = 4 I_{th}

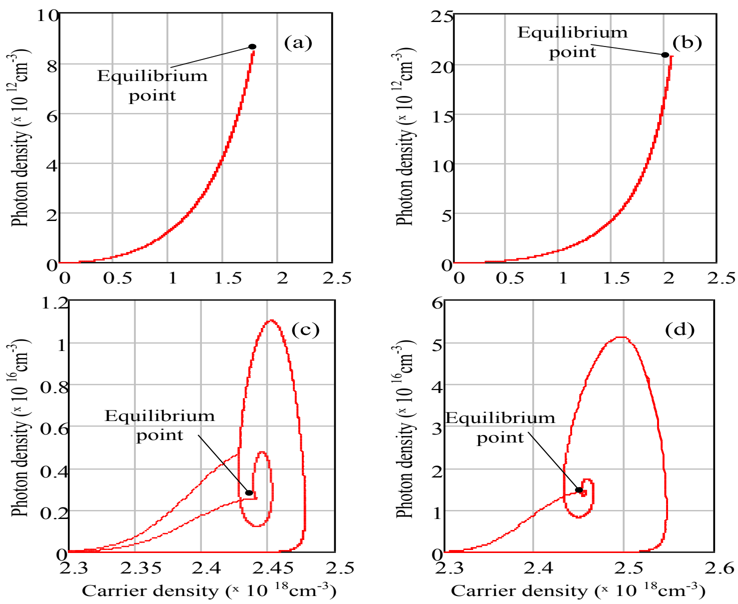

Figure 5: DFB laser phase plane at: (a) I_{inj} = 1.5 I_{th}, (b) I_{inj} = 2 I_{th}, (c) I_{inj} = 3 I_{th} and (d) I_{inj} = 4 I_{th}

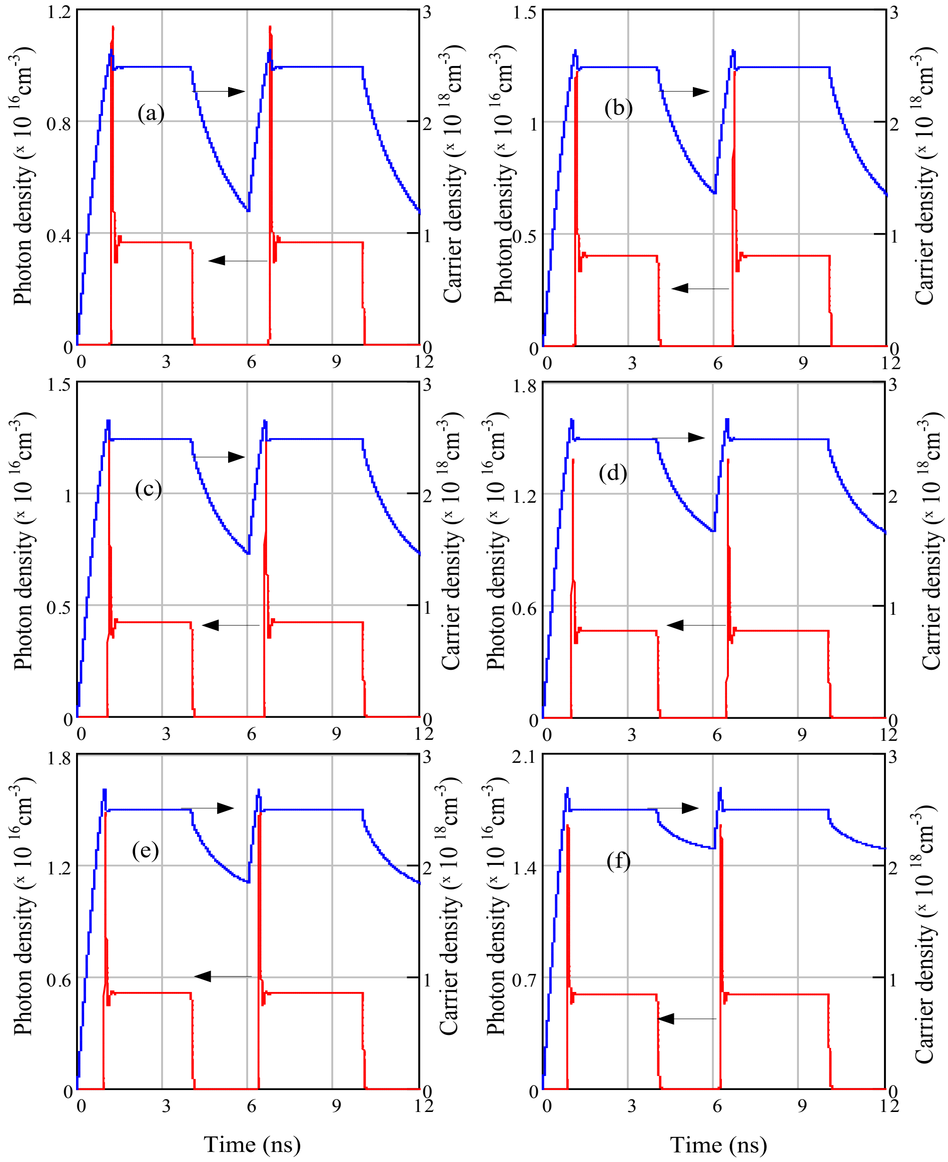

Figure 6: Transient response for DFB at (a) I_{bias} = 0, (b) I_{bias} = 0.3 I_{th}, (c) I_{bias} = 0.5 I_{th}, (d) I_{bias} = 0.7 I_{th}, (e) I_{bias} = 0.9 I_{th} and (f) I_{bias} = 1.1 I_{th}

Figures 6 and 7 show the effect of the basing current (I_{bias}) on the transient phase plane responses, respectively. Results showed that, by increasing the biasing level from I_{bias} = 0 to 1.1I_{th}, the TRO value has reduced from the 0.47 to the 0.21 ns. In addition, results show that the T_{Delay} has reduced from the 1.24 to the 0.91 ns. Conversely, the peak amplitude of the P has increased from the 1.1 x 10^{16} cm^{-3} to the 1.71 x 10^{16} cm^{-3}.

This effect was observed on the Q-point response, as shown in Figure 6. Where increasing the bias current has excited to increase the number of photons inside the active region, thus exceed the threshold, relaxation oscillation period and then reach to the stability stead.

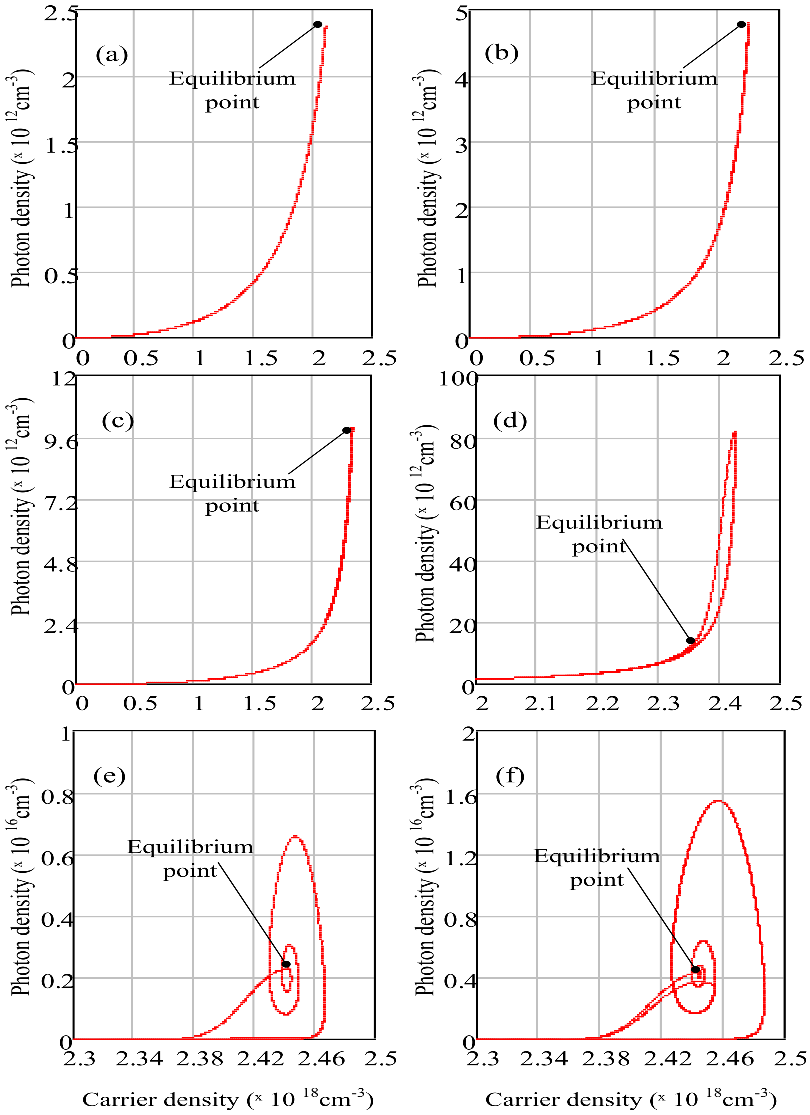

Figure 7: DFB laser phase plane at: Ibias = 0, (b) Ibias = 0.3 Ith, (c) Ibias = 0.5 Ith, (d) Ibias = 0.7Ith, (e) Ibias = 0.9Ith and (f) Ibias = 1.1It$_h$

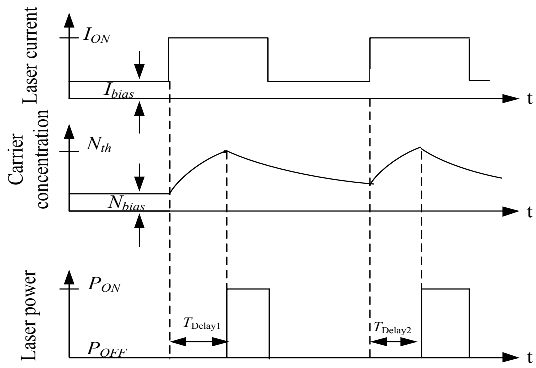

Figure 8: Effect of bias current (I_{bias}) on the SDLs transient response [6, 7]

Practically, the exact value of the T_{Delay} is strongly depended on the injected levels for the I_{inj} and the I_{bias}. The effect of the I_{bias} on the laser response can be clarified as: when the SDL is biased at sub-I_{th} level, N will take some times to rise to N_{th}, which results in delay (i.e., T_{Delay}) in the laser output. The lasing starts for emitting after the pulses have been injected (i.e., $N \geq N_{th}$), then, the output power (P_{out}) appears after the T_{Delay} period and when the injection is over, then P_{out} will begin to disappear. Then, N begins to decrease gradually. Thus, if the next pulse has injected before the N reaches its steady state, the T_{Delay} will be shorter (i.e., $T_{Delay2} < T_{Delay1}$) as illustrated in Figure 8.

Figures 9 and 10 are shows the effect of temperature (T) variation on the transient and the phase plane responses of DFB laser, respectively. Results show that the peak amplitude of P, TRO, and T_{Delay} at room temperature (i.e., at 25 ºC) is around 5.1 x 10^{16} cm^{-3}, 0.17 ns, and 0.88 ns, respectively. As shown, by changing T from 10 to 80 ºC, the peak amplitude of P, is reduced from 1.22 x 10^{16} to 0.84 x 10^{16} cm^{-3}. In contrast, T_{Delay} and TRO are significant increases from 1.21 to 1.45 ns and from 0.22 to 0.56 ns, respectively.

This reduction in the P value is due to the increase of the total loss (α_T) with T [8, 9]. Where by increasing T from 10 to the 80 ºC, α_T is increased gradually, which leads I_{th}, T_{Delay}, and TRO to increase; thereby, the amplitude of P is reduced [8, 9]. Thus, this effect is reflected in the Q-point movement, as shown in Figure 10.

The temperature (T) effect can be explained more precisely as: due to the temperature dependence (TD) for the total laser loss [8, 9]; with changing T, the internal fluctuations increases gradually leads to increase the total laser loss (α_T) [8, 9].

This increment in the α_T leads to reduce the photon lifetime and then results in increases in the threshold carrier density (N_{th}) [8, 9].

And as is known, any increase in Nth value at constant I_{inj}; meaning that the laser will be working for a long time within the transitional period (i.e., unstable Q-point region) and needs to more time to operate or may fail to work if I_{th} increases with T to a value above I_{inj}. This case is very important; it may push the laser to operate in the improper region leads to an increase in the transient period or make it in the off mode.

Finally, gain compression factor (ε) represent one of the important parameters that affect the SDL dynamic responses [4, 7, 8]. Figures 11 and 12 are shows the DFB transient and phase plane responses for different values of ε at I_{bias} = 0. Results show, as the ε increases from zero to 0.5 x 10^{-17}, 1 x 10^{-17}, and 1.5 x 10^{-17}, the sinusoidal oscillation is damped significantly and the TRO has reduced, leading to a larger period of stabilized for the P. This period will be sufficient to move the Q-point and to arrival to the stability zone as shown in Figures 10 and 11, respectively. Conversely, any changing in the ε value will not effect on the T_{Delay}. In addition, the P value is not affected significantly by the changes of the ε since the N is stabilized. This can be explained as: during the T_{Delay}, the laser exhibits a normal transient period response; where N increases with a rate in proportional to the carrier lifetime. As soon as N reaches up, after a specified T_{Delay}, the stimulated emission occurs, and after some TRO, the P stabilizes at its steady-state value, which it corresponds to the value of I_{inj}.

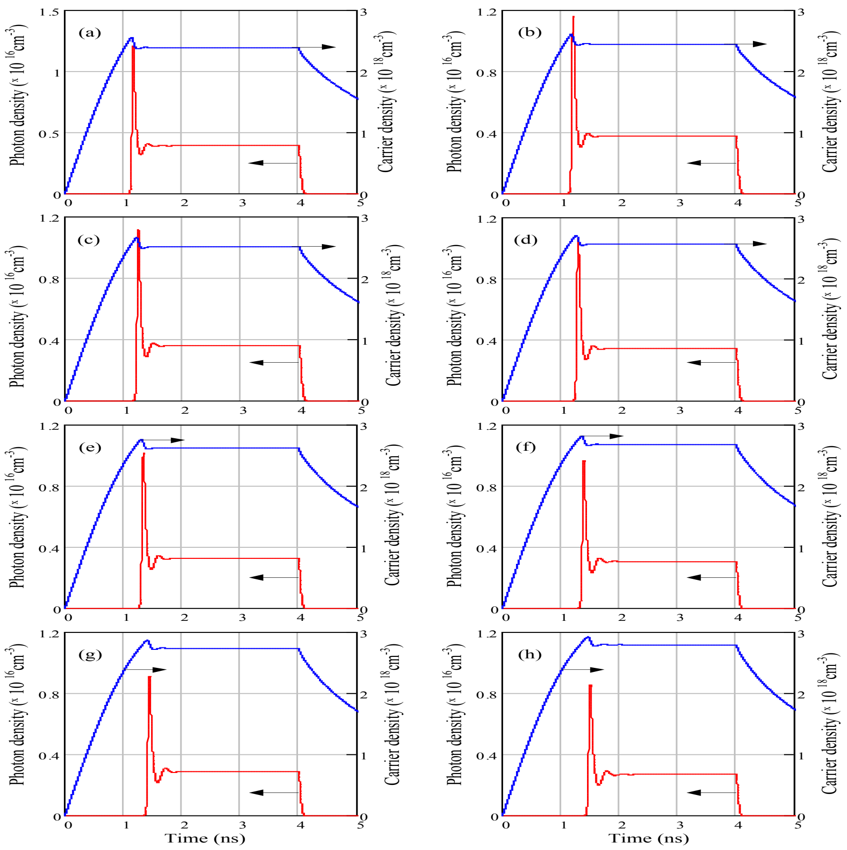

Figure 9: Transient response for DFB laser at: (a) T = 10 °C, (b) T = 20 °C, (c) T = 30 °C, (d) T = 40 °C, (e) T= 50 °C, (f) T = 60 °C, (g) T= 70 °C and (h) T = 80 °C.

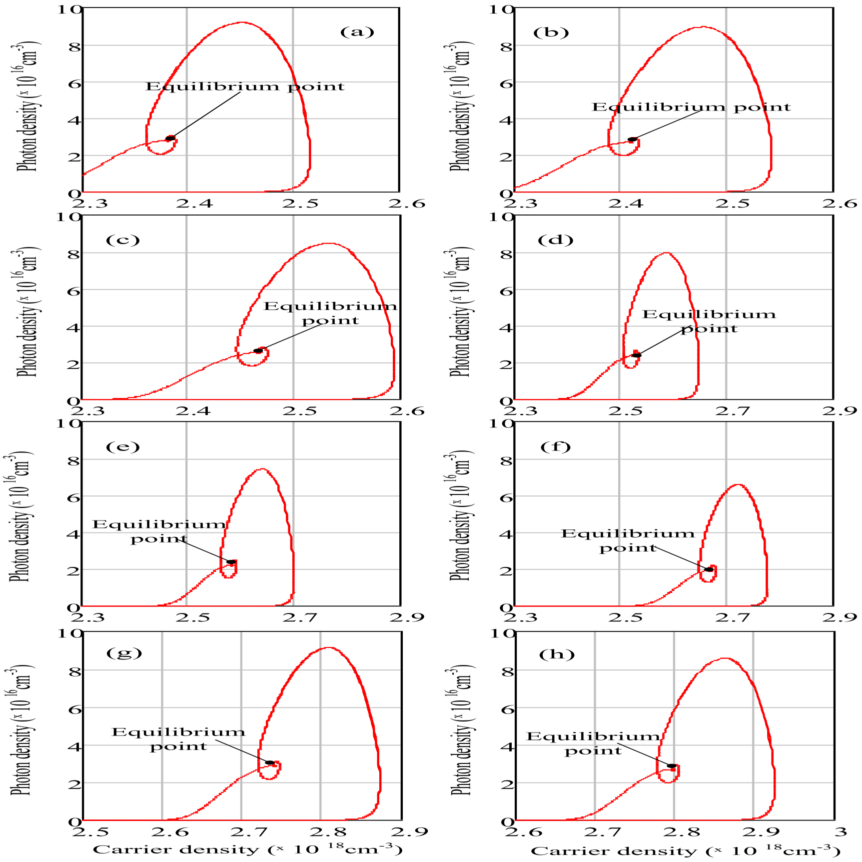

Figure 10: DFB laser phase plane at: (a) *T* = 10 °C, (b) *T* = 20 °C, (c) *T* = 30 °C, (d) *T* = 40 °C, (e) *T*= 50 °C, (f) *T* = 60 °C, (g) *T*= 70 °C and (h) *T* = 80 °C.

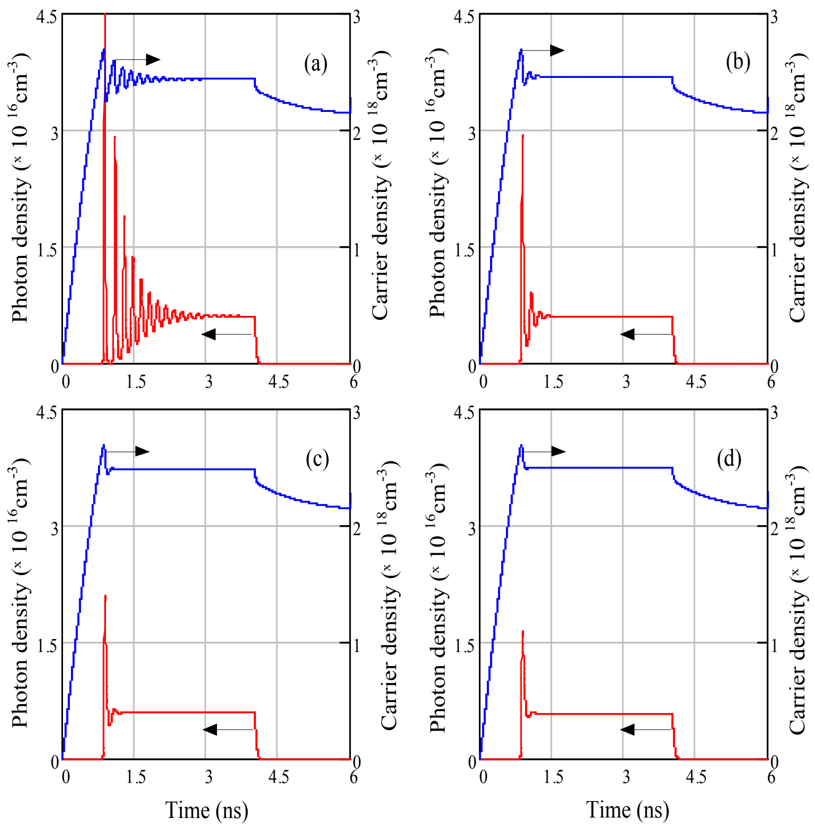

Figure 11: Transient response for DFB laser at: (a) ε = 0, (b) ε = 0.5 ×10^{-17}, (c) ε = 1×10^{-17} and (d) ε = 1.5×10^{-17} cm^{3}.

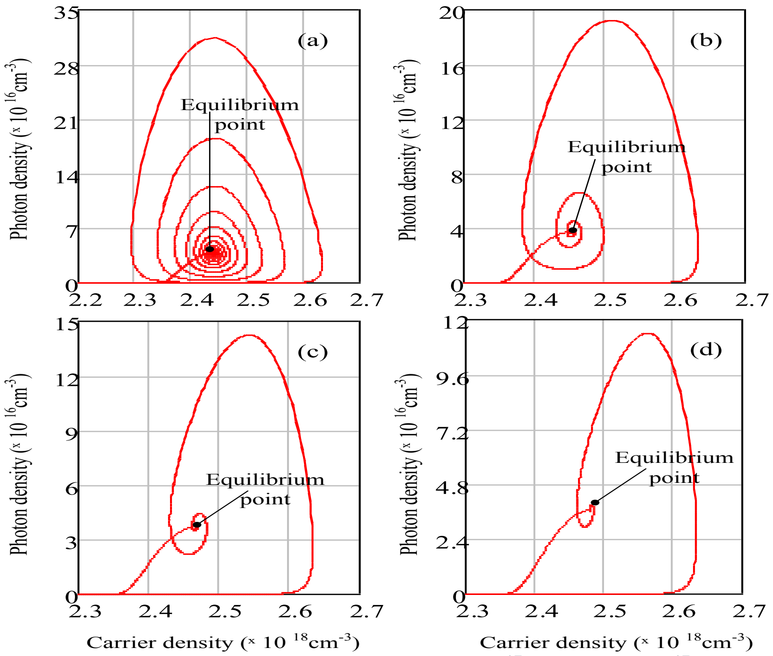

Figure 12: DFB laser phase plane at: (a) ε = 0, (b) ε = 0.5 ×10^{-17}, (c) ε = 1×10^{-17} and (d) ε = 1.5×10^{-17} cm^{3}.

4. Conclusion

In this paper, the DFB Q-point has been controlled successfully by using a new methodology based on a numerical optimization analyses. The analysis was based on investigating the effect of laser injection current (I_{inj}), dc-bias level (I_{bias}), temperature (T) variation and gain compression factor (ε) on the transient response of DFB laser model. Analyses have shown that I_{inj}, I_{bias}, T and ε are played an important role in controlling the Q-point operation region. Results show by increasing the I_{inj} and/or the I_{bias}, the TRO and the T_{Delay} are reduced significantly. Conversely, the TRO can be reduced significantly by increasing the ε value, while the T_{Delay} will not affect. In addition, result show that the temperature (T) variation affects the Q-point and the transient response significantly, were at the high T variation; the TRO and the T_{Delay} are increased which it may lead the laser to fail in operating normally.

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