Delay Time Reduction in VCSELs by Optimizing Laser Parameters

Hisham K. Hisham

Department of Electrical Engineering, Faculty of Engineering,

Basra University

Basra, Iraq

E-mail: husham_kadhum@yahoo.com.

Abstract

An extensive analysis on reducing the turn-on time delay (t_{on}) in vertical cavity surface emitting lasers (VCSELs) has conducted successfully by considering all the recombination rate coefficients R(N) Besides the R(N) coefficients, the impact of other laser parameters such as, injection current (I_{inj}), laser cavity volume (V),mirror reflectivity (R), and operating temperature (T) also have investigated. Unlike pervious studies, the temperature dependence (TD) of t_{on} is calculated according to TD of laser parameters instead of well-known Pankove relationship. Results showed that, t_{on} can be reduced by increasing the I_{inj} and/or the N_i. Meanwhile, the t_{on} increases by increasing the R(N) coefficients. Also, results showed that the t_{on} can be reduced by increasing the R-level or by optimizing laser cavity volume.

***Index Terms*—Fast response lasers, optimizing laser model, turn-on time delay, vertical cavity surface emitting laser (VCSEL), wavelength division multiplexing (WDM) systems.**

I. Introduction

The fulfillments of wavelength division multiplexing (WDM) and dense WDM (DWDM) are becoming urgent to support huge data transmission. To achieve that, a laser with very fast response, high wavelength stability, low chirp, and with reasonable cost is required. On the other hand, temperature variation leads to fluctuate in the laser operating frequency. This instability for the laser output with temperature variation makes it unsuitable for the requirements of WDM/DWDM systems [1].

Due to their diverse applications in optical network, recently years seen a rapid growth in vertical cavity surface emitting lasers (VCSELs) technology. VCSELs have high Possibilities as cheap light sources for fiber-optical communication systems due to their ability for direct laser-to-fiber coupling with high single-mode output power for data links and fiber optics systems [2, 3].

Reality, many studies have been made to transfer the VCSELs applications from the short to long-wavelength data transmission. However, due to their short active region; they have the disadvantage of high temperature sensitivity [4-5].

Generally, in semiconductor laser diode (SLD); the carrier population (N) is needed a certain time to reach its threshold value (N_{th}) known as time delay (t_{on}) [6, 7]. This time is due to the change of SLD's injection current (I_{inj}) from its initial value (I_o) to any current value (I) greater than the laser threshold current (I_{th}). Practically, this delay may results in poignant error [6]. In addition to that, the laser may fail to operate due to the long t_{on}

and high N_{th} [8, 9]. Therefore, time delay represents a significant parameter in determining the performance of SLDs. To this day, many studies have been performed on reducing t_{on} for several types of SLDs [7-10]. However, based on our best knowledge, there is no comprehensive study reported on time delay characteristics of VCSELs, which is the focus of this paper.

Primarily, the laser's time delay is strongly depended on the recombination rate coefficients ($R(N)$) define as [6]

$$R(N) = A_{nr}N + BN^2 + CN^3 \quad (1)$$

In (1), A_{nr}, B and C are defined as the non-radiative, radiative and Auger coefficients for recombination rate, respectively. Some researcher [8, 9] have been solved equation (1) by neglecting one or two of $R(N)$ coefficients. In addition to the lack of precision in the results have been obtained, these studies ignored the impact of the coefficients have been neglected. In [6], equation (1) solved by assuming $R(N)$ is equal to $A_{nr}N$ or $BN^2$and in [7], Krehlic and Sliwcznski calculated t_{on} by assuming that the parameters A_{nr} and B in Equation (1) are equal to zero. While in [9], the researchers solved equation (1) by considering all the $R(N)$ coefficients. However, the results reported in [8], on the effect of $R(N)$ coefficients on t_{on} are generally not accurate compared to exact model [10]. This is because in practice, any increase in the $R(N)$ coefficients increases the I_{th}, thereby t_{on} is increased. On the other hand, t_{on} is temperature dependent (TD) and it increases with the increase of temperature due to the increment of N_{th} and I_{th}, which both are TD [5, 6]. However, there are no studies have been reported on the effect of temperature variation on the time delay.

In this paper, a comprehensive study on the turn-on time delay (t_{on}) characteristics of VCSELs is successfully investigated by considering an exact numerical expression. The paper is organized as follows. Section II covers VCSEL model, including the threshold carrier density and photon lifetime computing. The t_{on} expression is presented by deriving an exact numerical expression in terms of the $R(N)$ coefficients (A_{nr}, B, and C), carrier density (N), injection current (I_{inj}), and temperature (T) presented in Section III. Section IV presents brief discussions on the obtained results. Finally, conclusions are presented in Section V.

II. Threshold Carrier Density and Photon Lifetime of VCSEL Model

A schematic diagram of the VCSEL model is shown in Figure 1 by assuming a uniform gain structure. The amplification inside the active region is generated by the optical feedback which is providing by the two mirrors, front with reflectivity R_f and rear with reflectivity R_r. The output power is emitted perpendicular from the layers.

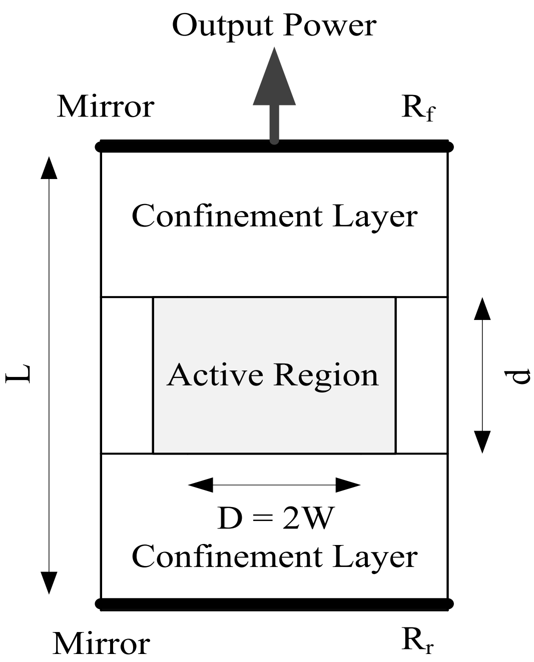

Figure 1 VCSEL structural model

By taking the temperature effect, the laser threshold current [5, 6] rewritten as

$$I_{th}(T) = eVN_{th}(T)R(T, N_{th}(T)) \qquad (2)$$

where e is the charge of electron, V is the active region volume and $R(T, N_{th}(T))$ is the TD form of Eq. (1) [5, 6], which can be rewritten as

$$R(T, N_{th}) = A_{nr} + BN_{th}(T) + C(T)N_{th}^2(T) \qquad (3)$$

where $C(T)$ describe the TD Auger process. The $N_{th}(T)$ in Eq. (3) is the TD carrier density equation at threshold condition [10] can be defined as

$$N_{th}(T) = N_t(T) + \frac{1}{\Gamma v_g a(T)\tau_p(T)} \qquad (4)$$

where $N_t(T)$, $a(T)$ and $\tau_p(T)$ are the carrier density, gain constant, and life time for photon under the effect of temperature, respectively. Γ (= d/L) denotes the confinement factor and v_g is the group velocity. The temperature effect on the delay time of VCSEL is investigated according to [3]. Since the temperature affects the photon lifetime in Eq. (4), thus the $\tau_p(T)$ can be modeled as [6]

$$\tau_p(T) = \frac{1}{v_g \alpha_{tot}(T)} \qquad (5)$$

where α_{tot}(T) is the TD laser cavity total loss that is defined as [6]

$$\alpha_{tot}(T) = \alpha_{int}(T) + \frac{1}{L}\ln\left(\frac{1}{R}\right) + \Gamma\alpha_d \qquad (6)$$

where $\alpha_{int}(T)$ is the TD internal cavity loss, $((1/L)\ln(1/R))$ is the mirror loss, $R = (R_f.R_r)^{1/2}$ and α_d is the diffraction loss defined by [11]

$$\alpha_d = -\frac{1}{d}\ln\left(\frac{2}{\left(2 + 3\left(\frac{2(L-d)}{kW^2}\right)^2\right) + \left(\frac{2(L-d)}{kW^2}\right)^4}\right) \qquad (7)$$

Where k (=$2\pi n/\lambda$) is the propagation constant, n is the effective refractive index and λ is the lasing wavelength.

III. Delay Time of VCSEL Model

The time taken for stimulated emission process to start is the delay time (t_{on}), where during this time, the photon density will stay essentially zero [5, 6]. The carrier density rate equation can be written as [5, 6, 10]

$$\frac{dN}{dt}=\frac{I_{inj}}{eV}-N\left(A_{nr}+BN+CN^2\right)-g\frac{N-N_o}{1+\varepsilon P}P \qquad (8)$$

where ε is the nonlinear gain factor and P is the photon density, respectively. In the time period ($0 < t < t_{on}$), the stimulated emission rate can be neglected because the photon density is essentially zero. Thus, the carrier density rate equation can be rewritten as [5, 6, 10]

$$\frac{dN}{dt}=\frac{I_{inj}}{eV}-A_{nr}N+BN^2+CN^3 \qquad (9)$$

It is known that t_{on} is the time needed for N to increase from a specified initial value (N_i) to threshold value (N_{th}). According to that, t_{on} is calculated by integrating Eq. (11) [8]

$$t_{on}=\int_{N_i}^{N_{th}}\frac{eV}{I_{inj}-eVN(A_{nr}+BN+CN^2)}dN \qquad (10)$$

Equation (10) is numerically solved to investigate the time delay of VCSEL. The numerical solution for Eq. 10 is given in [10].

IV. Results and Discussion

Table I shown the VCSEL parameters used in the analysis. All these values are fixed throughout the paper, except otherwise stated.

Table I
Parameters of VCSEL model

FP Parameters	Description
$N_o = 1\times10^{24}$ m^{-3}	Transparency carrier density
$A_{nr} = 1\times10^{8}$ sec^{-1}	Non-radiative coefficient
$B = 1\times10^{-16}$ m^3/sec	Radiative coefficient
$C = 3\times10^{-41}$ m^6/sec	Auger coefficient
$\alpha_{int} = 1000$ m^{-1}	Internal cavity loss
$a_o = 2.5\times10^{-20}$ m^2	Differential gain
$I_{inj} = 4\ I_{th}$	Injection current
$\lambda = 0.87$ µm	Laser wavelength

Figure 2 shows the effect of I_{inj} on t_{on} for VCSEL model as a function of the carrier density ratio ($\rho = N_i/N_{th}$) at room temperature (T_o), where in this study is assumed $T_o = 25^oC$. The result shows that by the increase of ρ, the t_{on} is reduced. This result is entirely consistent with [6]. On the other hand, by increasing I_{inj}, the t_{on} is reduced. The effect of I_{inj} is reduced when the laser is operated at high bias level or high ρ, and vice versa. This behavior is consistent with the measured results that are obtained in [9].

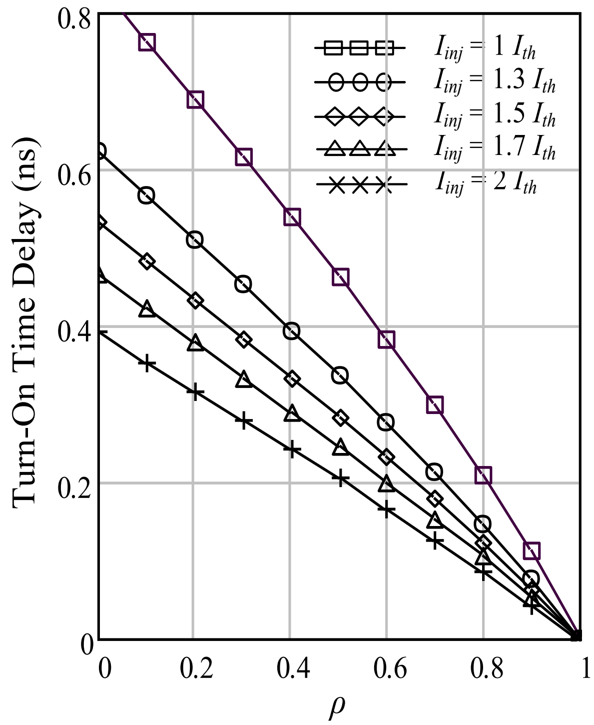

Figure.2 Turn-on time delay as a function to ρ for different value for I_{inj}

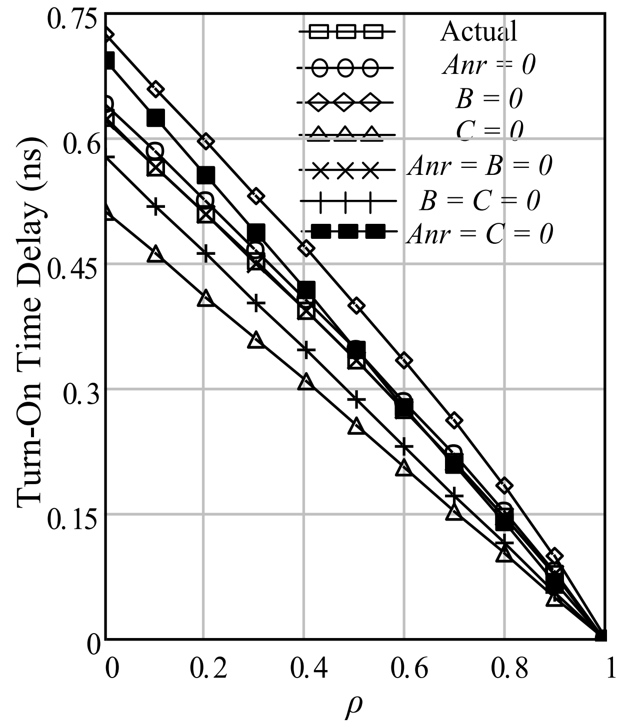

Figure 3 Comparison between the actual turn-on time delay and the approximation model as a function of ρ

Figure 3 shows comparison between the actual t_{on}, calculated in this study and the approximated expression, where $A_{nr} = C = 0$ [6], $B = C = 0$ [6], and $A_{nr} = B = 0$ [6]. The result shown is based on $I_{inj} = 1.3I_{th}$ at T_o. As mentioned in the introduction, doing the analysis by neglecting one or two from the $R(N)$ coefficients leads to obtaining an approximate results do not represent the true reality. This results is consistent with that given in [10] about the strong dependence of the t_{on} on the parameter C rather than the other recombination coefficients (A_{nr} and B).

Figure 4 shows the effect of temperature (T) variation on t_{on} as a function of ρ at $I_{inj} = 1.3I_{th}$. As shown in the figure, by increasing T from 25 to 75 ºC, the t_{on} is significantly increased. It is clear that T significantly affects the t_{on} due to the strong TD of N_{th} [10]. However, the effect of temperature can be reduced by increasing ρ. This is because when $\rho \rightarrow 1$, i.e. $N_i \rightarrow N_{th}$, therefore, $t_{on} \rightarrow 0$. Thus, when the laser is turned on from an initial value of the N closed to N_{th}, the t_{on} is significantly low [5, 6].

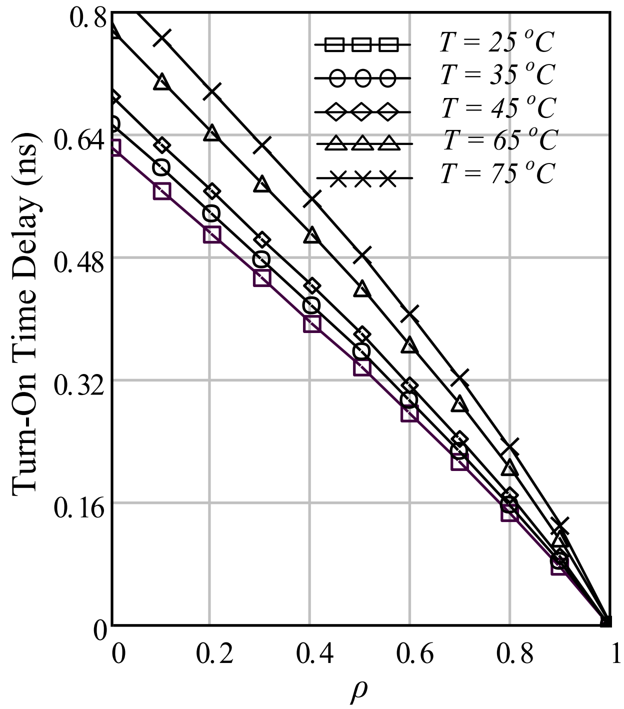

Figure 4 Effect of temperature on turn-on time delay

The good understanding for the *R*(*N*) mechanisms in SLDs is essential for designing LDs with high static and dynamic performance. Practically, it is necessary to reduce the non-radiative processes for increasing the SLDs efficiency [11]. Figures 5(a), (b) and (c) show the effect of the *R*(*N*) coefficients A_{nr}, *B*, and *C* on the t_{on} as a function of ρ, respectively. As shown in Figure 5, by increasing any of the *R*(*N*) coefficients, the t_{on} is increased due to the increase of the time of *R*(*N*) This is because by increasing the *R*(*N*) value, I_{th} is increased according to Eq. (2).

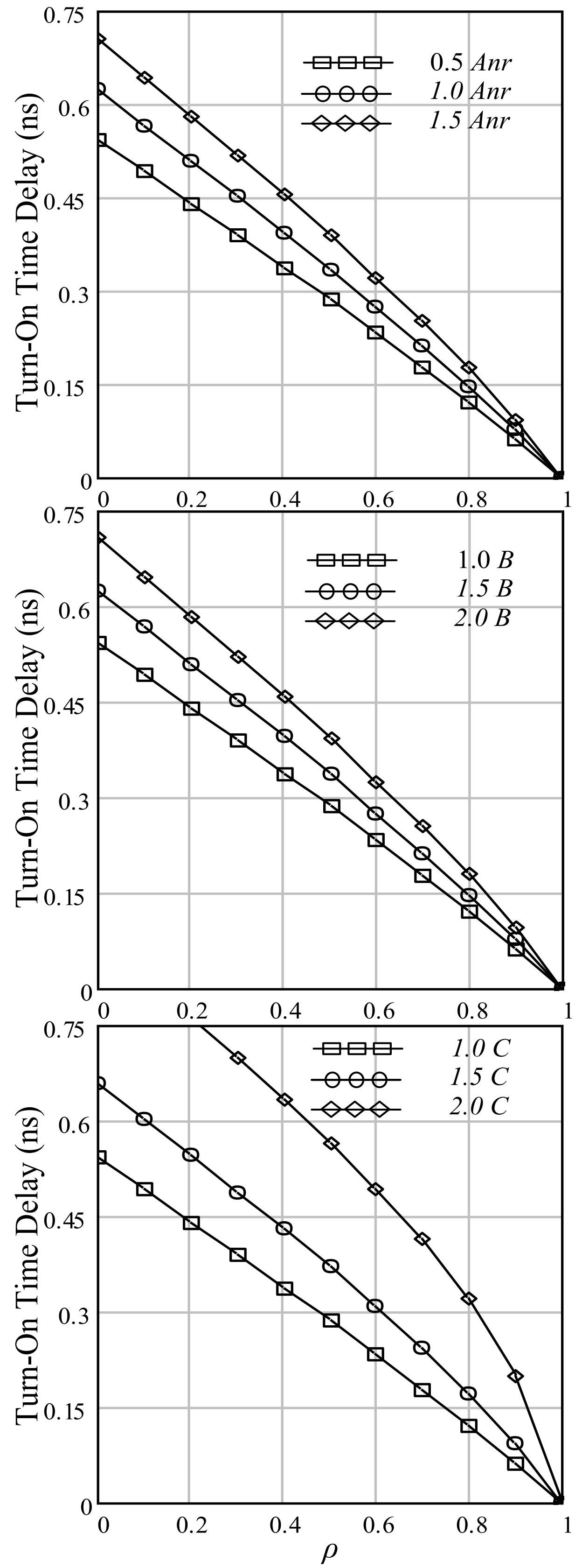

Figure 5 Effect of *R*(*N*) coefficients on turn-on time delay as a function of ρ

The laser cavity volume represents one of most important parameters that determined the laser performance due to the direct impact on the laser threshold current. Figure 6 (a), (b) and (c) show the effect of the VCSEL cavity volume parameters *D*, *d*, and *L* on the t_{on} as a function of ρ, respectively. Results shown, the delay time takes relatively a small value at small *D* and gradually increases by increasing *D*. This effect is due to increase the total loss in laser cavity which leads to increase the laser threshold current. From other hand, results shown that the worst case by increasing *d* from 2 µm to 6 µm is occurs when *d* = 2 µm. Conversely, by increasing *L* from 7 µm to 20 µm there is no significant effect on t_{on}.This is because at high value for *D*, the diffraction loss α_{dif} (Eq. (7)) will dominate and leads to increase the total cavity loss α_{tot}, then increasing the t_{on}.

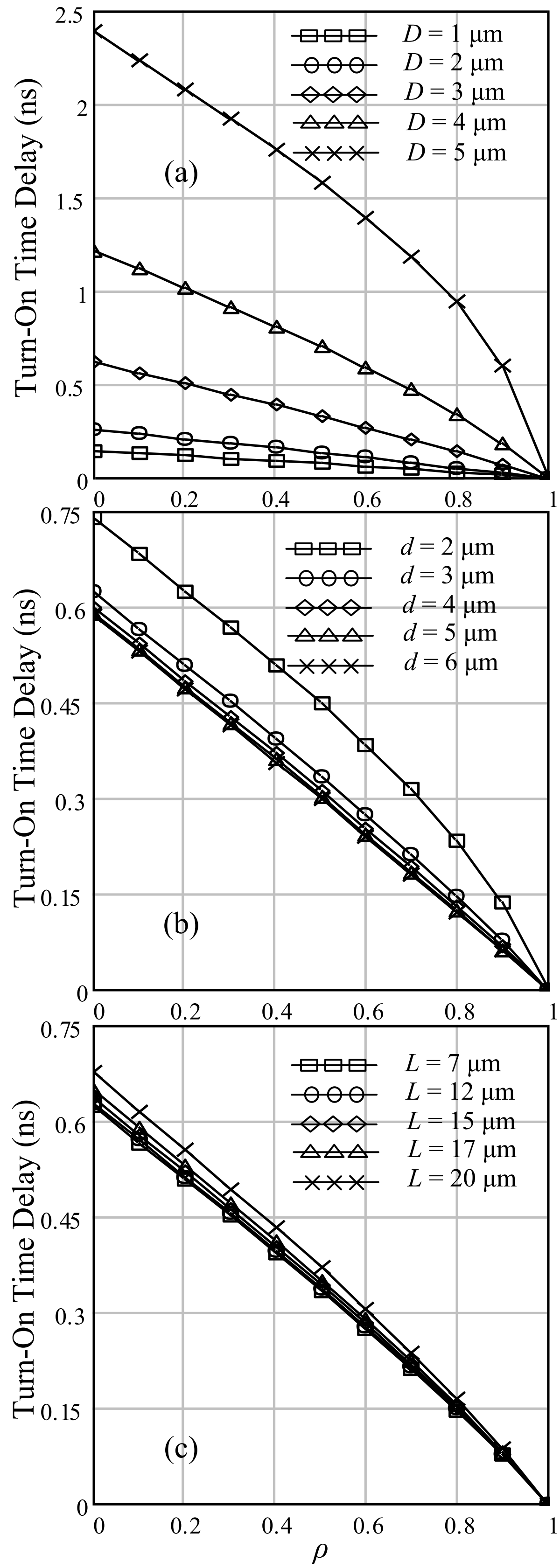

Figure 6. Effect of VCSEL cavity volume coefficients on turn-on time delay

Finally, the effect of mirror reflectivity (R) on t_{on} as a function of ρ at T_o and $I_{inj} = 1.3I_{th}$ is presented in Figure 7. As shown, by increasing the R level, the t_{on} reduced. This is because any increase in the reflectivity level leads to reduce the total cavity loss of the laser diode [5, 6, 10], which caused to increase the photon lifetime and decrease the threshold carrier density, thus, reduce the laser threshold current as given in Eq. (2) which leads to reduce the laser t_{on} .

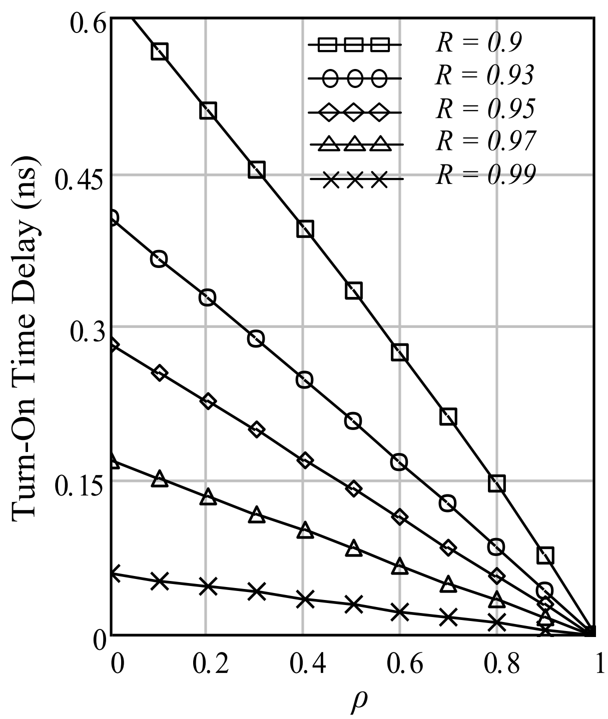

Figure 7. Effect of mirror reflectivity on turn-on time delay

V. Conclusion

Unlike the previous studies have reported in [6-9], in this paper for the first time, a comprehensive analysis on reducing the turn-on time delay (t_{on}) in vertical cavity surface emitting lasers (VCSELs) has conducted successfully. It has been shown that the t_{on} of VCSEL can be reduced by reducing any of the $R(N)$ coefficients. In addition, t_{on} has increased by increasing the operating temperature (T). However, the temperature effect can be reduced by increasing the laser injection current (I_{inj}) and/or ρ. Besides of I_{inj} and ρ, the t_{on} also can be reduced by increasing the laser mirror reflectivity (R). Moreover, the performance of VCSEL can be improved by optimizing the VCSEL cavity volume parameters (D, d and L). The benefits of this study represent a good guideline to design and fabricate these advanced lasers for high speed data transmission systems.

References

[1] H. K. Hisham, A. F. Abas, G. A. Mahdiraji, M. A. Mahdi, A. S. Muhammad Noor, “Characterization of phase noise in a single-mode fiber grating Fabry–Perot laser” J. Modern Optic, vol. 59, pp. 393–401, 2012.

[2] H. K. Hisham, A. F. Abas, G. A. Mahdiraji, M. A. Mahdi, A. S. Muhammad Noor, “Relative Intensity Noise Reduction by Optimizing Fiber Grating Fabry-Perot Laser Parameters,” IEEE J. Quantum Electron., vol. 48, pp. 385–393, 2012.

[3] H. K. Hisham, A. F. Abas, G. A. Mahdiraji, M. A. Mahdi, F. R. Mahamd Adikan, “Optimizing the External Optical Cavity Parameters for Performance improvement of a Fiber Grating Fabry-Perot Laser,” Optical Review, In Press (2015).

[4] H. K. Hisham, A. F. Abas, G. A. Mahdiraji, M. A. Mahdi, F. R. Mahamd Adikan, “Frequency modulation response due to the intensity modulation of fiber-grating Fabry–Perot lasers”, J. Modern Optic., (2014).

[5] M. K. Liu, Principle and Applications of Optical Communication. The McGraw-Hill, USA, 1996.

[6] G. P. Agrawal, N. K. Dutta, Semiconductor Lasers, second ed. New York: Van Nostrand Reinhold, 1993.

[7] P. Krehlic, L. Sliwczynski, “Modeling of dynamic performance of semiconductor lasers under subthreshold biasing,” Opto-electron. Review, vol. 12, pp. 187–189, 2004.

[8] X. X. Zhang, W. Pan, J. G. Chen, H. Zhang, “Theoretical calculation of turn-on delay time of VCSEL and effect of carriers recombination,” Optics and Laser Technol., vol. 39, pp. 997–1001, 2007.

[9] P. Krehlic, L. Sliwczynski, “Laser driver with subthreshold laser bias and turn-on delay compensation by prejittering of the modulating current,” Int. J. Electron. Commun., vol. 60, pp. 331–337, 2007.

[10]H. K. Hisham, A. F. Abas, G. A. Mahdiraji, M. A. Mahdi and F. R. Mahamd Adikan, ”Characterization of Turn-On Time Delay in a Fiber Grating Fabry-Perot Lasers”, IEEE Photon. Journal, vol.4, pp. 1662-1678, 2012.

[11]Volet, E. kapon,“Turn-on delay and Auger recombination in long wavelength vertical cavity surface emitting lasers,” Appl. Phy. Lett., vol. 97, pp. 131102-3, 2010.