Abstract: In this paper, a full analytical and exact expression form of turn-on time delay, $t_{on}$, of uncooled semiconductor laser diode has been presented in terms of nonradiative, $A_n$, radiative, $B_n$, Auger recombination coefficients, $C_{Auger}$, cavity dimensions, threshold carrier density, $N_{th}$, injection current, $I_{inj}$, number of "0" bits preceding the considered bit, $N_0$, bit-rate, $B_r$ and temperature of operation, $T$. Also, we will include, in addition to the mentioned parameters, the external optical feedback (EOF) parameters i.e., external reflectivity, $r_{ext}$ and phase of reflected light, $f$. The effect of EOF on $t_{on}$ was studied corresponding to its effect on threshold carrier density, $N_{th}$, and its initial value, $N_{ini}$, and in presence of different values of temperature degrees. Furthermore, we found, through the mathematical analysis and simulation results, that $N_{ini}$ is characterized by what we called it "undefined region" in the region around specified values of $r_{ext}$ and $f$.

Key words: External optical feedback, temperature effect, turn-on time delay, semiconductor laser diode.

INTRODUCTION

Semiconductor laser diodes (SLDs) are popular as carrier generators for optical telecommunications. Their proneness to exhibit complicated dynamical responses to external perturbations can hamper technological progress in conventional FM data transmission (Nizette, 2004). SLDs are known to be extremely sensitive to EOF that arises in practical applications due to the back-reflections from other optical components, such as lenses and fibers (Kapusta, et al., 2006). The influence of EOF on the dynamic response of SLD has been extensively studied (Nizette, M. and T. Erneux, 2004; Kapusta, E.W., D. Luerben, 2006; Al-Azab, J.M. and A.M. El-Nadi, 2007; Sato, H. and J. Ohya, 1985; Agrawal, G.P. and N.K. Dutta, 1986; Helms, J. and K. Petermann, 1989; Kakichida, H. and J. Ohtsubo, 1994; Petermann, K., 1995; Kallimani, K. and M.J. O'Mahony, 1998; Lawrence, J.S., 2000; Lawrence, J.S. and D.M. Kane, 2000; Mortliber, G., 2002; Osmundsen, J.H. and N. Gade, 1985; Langley, L.N. and K.A. Shore, 1993; Langley, L.N. and K.A. Shore, 1992) where it has been found to induce a variety of effects, either detrimental or advantageous to the SLDs operating characteristics, depending on the feedback level. Also, the operation of SLD with phase conjugate feedback (PCF) has attracted attention. PCF is found to induce more complex dynamic behavior, and to provide better mode coupling for broad area and SLD array (Lawrence, J.S. and D.M. Kane, 2000). The effects of EOF include mainly linewidth, threshold gain, output power and spectrum. The route to chaos is the term used to denote a detailed description of the SLD output with EOF where the diode is brought from a stable to unstable state (Al-Azab, J.M. and A.M. El-Nadi, 2007). From regimes I to IV, the SLD's behavior evolves from stable operation, through mode hopping, to lowest linewidth mode operation and then "coherence collapse" which is characterized by a laser linewidth that is broadened by several orders of magnitude (Langley, L.N. and K.A. Shore, 1993). It is known that the performance of high-speed, intensity modulated, direct detection systems is critically dependent on the characteristics of SLD (Al-Azab, J.M. and A.M. El-Nadi, 2007; Sato, H. and J. Ohya, 1985; Obermann, 1996). The turn-on time delay, $t_{on}$, and its jitter plays a significant role in determining the system performance of SLD and has been studied both experimentally and theoretically (Langley, L.N. and K.A. Shore, 1993; Langley, L.N. and K.A. Shore, 1992; Pepeljugoski, P., D. Kuchta, 1996;
Stephan, T., K. Hinton, 1995; Obermann, K., S. Kindt, 1996; Ming, M. and K. Liu, 1996; Curter, D.M. and K.Y. Lau, 1995). To our best Knowledge, most of the published papers that interested with $t_n$, are based on numerical calculations, experimental works or a very approximated assumptions. The effect of EOF on $t_n$ has been studied mainly in (Langley, L.N. and K.A. Shore, 1993; Langley, L.N. and K.A. Shore, 1992). EOF leads to increase in average $t_n$ and the jitter (Langley, L.N. and K.A. Shore, 1993). In addition, when EOF increases, the average $t_n$ may increase or decrease depending on the conditions of periodic and pseudorandom modulations that used in simulation (Langley, L.N. and K.A. Shore, 1992). In those papers and because of the used numerical model, the reader could not be familiar with the role of SLD parameters specially the threshold carrier density which depends mainly on cavity parameters such as photon lifetime, $t_p$ and the gain coefficient, $g_0$ usually known as they are EOF-dependent parameters.

In (Hassan, M.R., 2008), we derived for the first time a full analytical and exact expression form of $t_n$ in terms of nonradiative, $A_n$, radiative, $B_n$, Auger, $C_{auger}$, recombination coefficients, cavity dimensions, threshold carrier density, $N_{th}$, (and in turn threshold current density, $I_{th}$), injection current, $I$, and temperature of operation, $T$. In this paper, we will include, in addition to the mentioned parameters, the EOF parameters i.e. external reflectivity including coupling losses, $r_e$, and phase of reflected light, $f$, to the analytical expression of $t_n$. In addition, the improvements in laser manufacture allow today operating uncooled direct modulated SLD over abroad temperature range. Given that, a strong cost reduction in optical systems can be achieved by eliminating costly laser temperature control. Uncooled SLDs have been considered as a key technology for future optical network systems (Morgado, J.P. and A.T. Cartaxo, 2003).

The aim of this paper is to study the effect of EOF on $t_n$ of uncooled SLD in the presence of temperature of operation. The effect of EOF on $t_n$ will be studied corresponding to its effect on $N_{th}$, which depends mainly on optical gain coefficient and photon lifetime knowing that they are EOF-parameters. The presented analysis allows the designers, firstly, to see a full and accurate mathematical picture about the role of each parameter appeared in carrier density rate equation and secondly, to calculate $t_n$ of SLD subject to EOF for various types of SLDs and at any value of wavelength or temperature degree.

**Characteristics of SLD with EOF: Gain Condition:**

The schematic structure of SLD with external cavity is shown in figure 1, where $r_1$, $r_2$ are field reflectivities of the laser facets (assumed $r_1 = r_2 = 0.566$), $L$ and $L_e$ are the lengths of SLD and external cavities.

It is well known that $t_n$ of a SLD can be obtained by integration of the carrier density, $N$, rate equation (with respect to $N$) from initial carrier density, $N_{th}$, to $N$, therefore, we believe that any physical-phenomena which affects $N_{th}$, then, affects $t_n$ certainly.

![Fig. 1: Schematic representation of the external cavity operated SLD.](image)

In this section, the effect of EOF on $N_{th}$ was presented in details. From the steady state analysis of carrier density rate equation, $N_{th}$ of single mode SLD can be written as (Agrawal, G.P. and N.K. Dutta, 1986; Ming, M. and K. Liu, 1996)

$$N_{th} = N_i + \frac{1}{\Gamma g_0 n_p \sigma_p}$$

where $N_i$ is the carrier density at transparency, $\Gamma$ and $v_p (= C/n_p)$ are the optical confinement factor and group velocity respectively, $C (= 3 \times 10^8 \text{ m/sec})$ is the speed of light in space, $g_0$ is the gain coefficient and $n_p$ is the group refractive index, assumed $n_p = 4$. 
Considering $\tau_p^f$ as the photon lifetime with EOF and substituting it instead of $t_p$ in eqn. (1), we can obtain expression of $N_a$ with EOF, $\bar{N}_{th}^f$. Furthermore we can include the effect of temperature of operation of uncooled SLD, therefore, temperature dependence (TD) of $\bar{N}_{th}^f$ can be written as

$$\bar{N}_{th}^f(T) = N_t(T) + \frac{1}{\Gamma g_e(T) \tau_p^f(T)}$$

(2)

where $N_t(T)$, $g_e(T)$ are the TD of $N_t$, $g_e$ and they can be expressed respectively as (Hassan, M.R., 2008; Morgado, J.P. and A.T. Cartaxo, 2003)

$$N_t(T) = \frac{T}{T_o} N_t(T_o)$$

(3a)

$$g_e(T) = \frac{T}{T_o} g_e(T_o)$$

(3b)

while we modeled $\tau_p^f(T)$ as

$$\tau_p^f(T) = \frac{1}{\Gamma g_e^f(T)}.$$  

$\bar{\alpha}_{total}^f(T) = \bar{\alpha}_{total}^f(T) + \alpha_f$

(4a)

where $\bar{\alpha}_{total}^f(T)$ is the TD of total cavity losses of SLD and $\alpha_f$ is the added losses due to EOF. $a_{int}(T)$ of distributed feedback (DFB) laser can be written, with assumption that the mirror loss is dominate, as (Morgado, J.P. and A.T. Cartaxo, 2003)

$$\bar{\alpha}_{total}^f(T) = \bar{\alpha}_{int}^f(T) + \frac{1}{2 L} \ln \frac{1}{r_1^2}$$

(4b)

where $\bar{\alpha}_{int}^f(T)$ is the TD of internal cavity losses which can be written as (Hassan, M.R., 2008; Morgado, J.P. and A.T. Cartaxo, 2003)

$$\bar{\alpha}_{int}^f(T) = \alpha_{int}^f \frac{T}{T_o}$$

(4c)

where $\alpha_{int}^f$ is internal cavity losses at room temperature, $T_o$ assumed $T_o = 25^\circ C$. 

In eqn (4a) above, $\alpha_f$ can be written as

$$\alpha_f = \frac{1}{2 L} \ln \frac{1}{R_{eff}}$$

(4d)

where
is the effective reflection coefficient of SLD (Sato, H. and J. Ohya, 1985; Kallimani, K. and M.J. O'Mahony, 1998; Osmundsen, J.H. and N. Gade, 1985) and \( \phi = \omega \tau_e \cdot \tau_e = \frac{2L}{C} \) is the round-trip time of photons inside the external cavity, knowing that \( \varphi = 0 \) or \( \pi \) (mod 2\( \pi \)) when the phase of reflected light is coherent or incoherent with the emitted field respectively. According to eqn. (2) and eqns. (4a-4e), analytical expression form of the TD of \( N_{th} \) of uncooled SLD with EOF can be written as

\[
N_{th}^f(T) = N_i(T) + \frac{\left( c_{ext}(T) + \frac{1}{2L} \ln \frac{1}{r_1^2} + \frac{1}{2L} \ln \frac{1+2r_2r_{ext}}{r_2^2 + r_{ext}^2 + 2r_2r_{ext}} \cos(\phi) \right)}{\Gamma g_o(T)}
\]

The initial carrier density, \( N_{th} \) (which will be used later in calculation of \( t_{th} \)) is given as (Curter, D.M. and K.Y. Lau, 1995)

\[
N_i = N_{th} \cdot e^{-\left( \frac{N_{bg}/Br}{\tau_e} \right)}
\]

where \( N_{bg} \) is the number of "0" bits preceding the considered bit, \( Br \) is the bit-rate and \( \tau_e \) is the carrier lifetime.

In (Curter, D.M. and K.Y. Lau, 1995) the authors assumed constant values of \( N_{th} \) and \( \tau_e \), however, here we modified the expression to

\[
N_{th}^f(T) = \beta(T) N_{th}^f(T)
\]

\[
\beta(T) = e^{-\left( \frac{N_{bg}/Br}{\tau_e} \right)}
\]

\[
T_s^f(T) = \frac{1}{A_{nr} + B_{r} N_{th}^f(T) + C_{auger} N_{th}^f(T)^2}
\]

where \( T_s^f(T) \) is the TD of carrier lifetime, \( T_e \), with EOF.

From eqns. 5 and 7 above, we note that when \( r_{ext} \to r_2 \) and \( \phi \to \pi \) results \( N_{th}^f|_{r_2} \to \pi \to \pi (\text{mod}\ 2\pi) \)

which means \( N_{th} \to \infty \). Also, \( \beta|_{r_2, \phi \to \pi (\text{mod}\ 2\pi)} = \beta|_{r_2, \phi \to \pi (\text{mod}\ 2\pi)} \to \pi (\text{mod}\ 2\pi) \)

then we have \( (N_{th} \to \infty) \times (\beta \to 0) \) or argumentatively \( \infty \times 0 \)!
From the mathematical description above, we conclude what we called it "undefined region" in $N_{au}$ characteristics around the mentioned values of $r$, and $f$ and this will be obvious later in the simulation results.

**Turn-on Time Delay on Uncooled SLD with EOF:**

In this section the effect of EOF on the $t_{on}$ of uncooled SLD with EOF is presented mathematically. In addition, the effect of temperature of operation of SLD will be included.

In (Hassan, M.R., 2008), we derived a full analytical and exact expression form of $t_{on}$ which can be written as

$$t_{on} = \left[ f(R, N)\right]_{R=R_1}^{\frac{d}{dN}} + \left[ f(R, N)\right]_{R=R_2}^{\frac{d}{dN}} \left[ f(R, N)\right]_{R=R_3}^{\frac{d}{dN}} \right|_{N=N_0} - \left[ f(R, N)\right]_{R=R_1}^{\frac{d}{dN}} + \left[ f(R, N)\right]_{R=R_2}^{\frac{d}{dN}} + \left[ f(R, N)\right]_{R=R_3}^{\frac{d}{dN}} \right|_{N=N_0} \right]$$

(10)

where

$$f(R, N) = \frac{-R}{C_{auger}} \ln \left[ \left( \left( 6 A_n C_{auger} Q - 2 B_r^2 Q \right) R + 3 Q C_{auger}^2 \right) N + \left( -9 A_n B_r - 9 Q C_{auger}^2 \right) R + Q B_r C_{auger} \right]$$

(11)

where $Q = qV$, $q$ is the electron charge and $V$ is the volume of the laser cavity and $R_i$ is the ith ($i = 1, 2, 3$) root of $G(Z)$ which can be written as

$$G(Z) = \left[ (4Q^2 A_n^2 C_{auger}) - (Q^2 B_r^2 C_{auger}^2) + (18QI_{tg} A_n B_r C_{auger}) - (4QI_{tg} B_r^2) + (27I_{tg}^2 C_{auger}^2) \right] Z^3$$

$$+ \left[ (3Q^2 A_n C_{auger}^2) + (Q^2 B_r^2 C_{auger}^2) \right] Z^2 \left[ C_{auger}^2 C_{auger} \right]$$

(12)

The roots of $G(Z)$ can be written as

$$R_1 = G_1 + G_2$$

(13a)

$$R_2 = \frac{-G_1 - G_2}{2} + \frac{j}{2} (G_1 - G_2)$$

(13b)

$$R_3 = \frac{-G_1 - G_2}{2} - \frac{j}{2} (G_1 - G_2)$$

(13c)

where

$$G_1 = \frac{(3I_{tg}) C_{auger} F_1}{D_1}$$

(14a)
and

\[ F_1 = Q^2 \left[ 9C_{auger} + \sqrt{3} \left( \frac{D_2}{D_1} \right)^{\frac{1}{2}} B_r^2 \right]^{\frac{1}{3}} \]  

(15a)

\[
D_1 = 27C_{auger}^2I_{inj} + 4C_{auger}A_{np}^2 + 18I_{inj}QA_{np}B_rC_{auger} - A_{np}^2B_r^2Q - 4I_{inj}QB_r^3 
\]

\[
D_2 = (9A_{np}B_rC_{auger}Q)^2 - 36A_{np}B_r^6C_{auger} + 4C_{auger}^2B_r^6 + 729C_{auger}^4I_{inj}^2 + 486C_{auger}I_{inj}QA_{np}B_r - 108I_{inj}QB_r^3C_{auger}^2 
\]

(15b)

Substituting eqns. (5) and (7) instead of \( N_{in} \) and \( N_i \) respectively in (10), we obtain a full analytical and exact expression form of \( t_i \) in terms of laser cavity parameters, EOF parameters, temperature of operation of SLD, number of bits and bit-rate. It is should be noted that in this paper we assume general values of EOF, in other words, \( r_i \) took smaller and larger values of the laser facet reflectivity, \( r_a \).

Notes:
(1) We used \( N_{in} \) rather \( I_a \) in order to give more physical form and that will be useful to complete the analysis further to include the next two stages (not indicated here). However, one simply can substitute \( t_i \) in or de \( t_i \) to calculate \( t_i \) in term of \( I_i \).

(2) We assumed \( I_{inj} \) in all results corresponding to \( I_{inj}(T_a) \) for SLD without EOF, i.e. \( I_{inj} \) is independent of temperature and EOF. This assumption is made according to the normal operation of laser source. In other words, the current source supplies a fixed value of injection current.

RESULT AND DISCUSSION

The effect of temperature of operation, \( T \), and external reflectivity, \( r_{ext} \), on the threshold carrier density, \( N_{th} \) is shown in figures 2a and 2b for \( \varphi = 0 \) and \( \pi \mod (2\pi) \) respectively. It is seen from both figures that when \( T \) increases then \( N_{th} \) increases due to increasing of carrier density at transparency, \( N_i \), decreasing of gain coefficient, \( g_i \), and increasing of cavity internal loss, \( a_c \). In figure 2a, \( N_{th} \) decreases as \( r_{ext} \) increases due to the increasing of \( \tau_i \), which increases due to the decreasing of \( a_{out} \). The latter decreases due to decreasing of added losses due to EOF, \( a_i \) (see eqn. (4a)). When \( \varphi = \pi \mod (2\pi) \), as shown in figure 2b, we note that \( N_{th} \) increases around \( r_{ext} = r_i = 0.566 \) due to large increasing of \( a_i \) around this value.

Figure 3 shows \( N_{th} \) as a function of \( r_{ext} \) and \( \varphi \) for \( T = 55^\circ C \) (selected arbitrary. It is seen from this figure, that when \( \varphi \approx \pi \mod (2\pi) \) and \( r_{ext} = r_i \) leads to \( N_{th} \rightarrow \infty \) because \( \tau_i = 0 \) due to \( a_{out} \rightarrow \infty \). This is clearly shown in the figure where the peak of graph is supposed to go to infinity.

Figure 4a and 4b show \( N_{thi} \) as a function of \( r_{ext} \) and number of "0" bits preceding the considered bit, \( N_{thi} \), for \( T = 25^\circ C \), \( \varphi = 0 \mod (2\pi) \) and bit-rate, \( B_r = 0.1 \) and 5 Gb/sec respectively. In figure 4a, we note that \( N_{thi} \) diminishes completely to zero through the first bit time interval \( T_s = \frac{1}{Br} = \frac{1}{0.1 \text{ Gb} / \text{s}} = 10 \text{ ns} \).
Fig. 2: Threshold carrier density vs. temperature of operation and external reflectivity for (a) $\phi = 0 \text{ mod } (2\pi)$ and (b) $\phi = \pi \text{ mod } (2\pi)$

Fig. 3: Threshold carrier density vs. phase of reflected light and external reflectivity for $T=55^\circ\text{C}$. The peak of the graph is supposed to go to infinity.

and in the same time $N_{ai}$ decreases as $r_{ai}$ increases from 0 to 1. When $Br$ increases to 5 Gb/sec (selected arbitrary as a high bit-rate), as shown in figure 4b, $N_{ai}$ diminishes through the five bits relatively slower than of pervious case. This is obvious by noting the term $b$ in eqn. (8a). Physically, when the bit time is shortened at high bit-rate, carrier concentration needs more time to decrease to low level, therefore, $N_{ai}$ has a significant value and depends strongly on bit time interval.

When the phase of reflected light becomes incoherent i.e. $\phi = \pi \text{ mod } (2\pi)$, as shown in figures 4c and 4d, we note what we call it as longitudinal jut in the region round $r_{ai} = r_{ei}$ (figure 4c) while this longitudinal jut is converted to longitudinal dip as the number of bits, $N_{ai}$, increases further to 5 bits. We called this region around as "undefined region" because approximately $N_{ai}$ is the resultant of multiplication of $\Psi$ with zero.
Fig. 4: Initial threshold carrier density vs. external reflectivity and number of "0" bits preceding the considered bit for $T=25^\circ$C and (a) $\varphi = \pi \mod (2\pi)$, $Br = 0.1$ Gb/sec (b) $\varphi = 0 \mod (2\pi)$, $Br = 0.1$ Gb/sec (c) $\varphi = \pi \mod (2\pi)$, $Br = 2$ Gb/sec and (d) $\varphi = 0 \mod (2\pi)$, $Br = 5$ Gb/sec.

Figs. 5a, 5b and 5c show $N_{th}$ as a function of $T$ and $r_{ext}$ for $\varphi = \pi \mod (2\pi)$ and different values of $Br$, i.e. 1, 1.7 and 2.5 Gb/s respectively. As noted in those figures with the help of eqn. (7) that when $T$ increases, then $N_{th}$ increases and $b$ decreases correspondingly. The latter decreases due to decreasing of carrier lifetime, $T_c$. So we are in front of an opposite change of $N_{th}$ and $b$ with $T$. The larger in change, its effect will dominate the overall effect and in turn, the undefined region. For instance, in figure 5a, there is a sharp decrease in the undefined region around $r_{ext} = r_{th}$, recalling that $Br = 1$ Gb/sec and $N_{th}$ decreases deeply as $T$ increases further to $85^\circ$C, in other words, the change (the decrease) of $b$ dominates the undefined region. When $Br = 1.7$ Gb/sec, $b$ will be less than the previous case and we note firstly that the increased $N_{th}$ dominates a part from the undefined region (relatively low temperatures range) but the increasing in $T$ leads more decreasing in $b$, therefore it dominates the another part of undefined region (note the grown dip at high
Fig. 5: Initial threshold carrier density vs. Temperature of operation and external reflectivity for $N_{th} = 1$, $\varphi = \pi \mod (2\pi)$ and (a) $Br = 0.5$ Gb/sec (b) $Br = 1$ Gb/sec (c) $Br = 2.5$ Gb/sec.

At larger value of $Br$, i.e. $Br = 2.5$ Gb/sec, as shown in figure 5c, we noted the longitudinal peak along the range of temperature. In other words, the increasing of $N_{th}$ with $T$ is larger than the decreasing of $b$ with $T$. We expect that at higher values of $T$, $b$ will decreases more and when its effect becomes larger than the effect of $N_{th}$, therefore, the undefined region begins to shape as dip rather than peak.

The effect of $N_{th}$, $Br$ and $T$, together with $\varphi$ (changes from 0 to $2\pi$) on the turn-on time delay, $t_\alpha$, are shown in figs 6, 7 and 8 for $r_{ext} = 0$ (without EOF) and figs. 9, 10 and 11 for $r_{ext} = 0.5$ respectively. It is noted from figure 6 that $t_\alpha$ increases with increasing of $N_{th}$ due to decreasing of $N_{th}$ while it increases, as shown in figure 7, with increasing of $Br$ due to increasing of $N_{th}$. Recalling that $N_{th}$ is unchanged because it does not depend on $N_{th}$ and $Br$. The effect of $T$ on $t_\alpha$ is shown in figure 8 for $Br = 1$ Gb/sec. and $N_{th} = 1$. It is noted that when $T$ increases, then $t_\alpha$ increases due to increasing of $N_{th}$ (and of course $N_{th}$). The latter increases with $T$ due to increasing of $N_i$ and decreasing of $g_n$ and $r_n$. 

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Fig. 6: Turn-on time delay vs. number of “0” bits preceding the considered bit and phase of reflected light for $r_{ext}=0$ (without EOF), $Br=1$ Gb/sec and $T=25^\circ C$.

Fig. 7: Turn-on time delay vs. bit-rate and phase of reflected light for $r_{ext}=0$ (without EOF), $N_{bit}=1$ and $T=25^\circ C$.

Fig. 8: Turn-on time delay vs. temperature of operation and phase of reflected light for $r_{ext}=0$ (without EOF), $N_{bit}=1$ and $Br=1$ Gb/sec.
Fig. 9: Turn-on time delay vs. number of "0" bits preceding the considered bit and phase of reflected light for $r_{in} = 0.5$, $Br = 1$ Gb/sec and $T = 25^\circ$C.

Fig. 10: Turn-on time delay vs. bit-rate and phase of reflected light for $r_{in} = 0.5$, $N_{in} = 1$ and $T = 25^\circ$C.

Fig. 11: Turn-on time delay vs. temperature of operation and phase of reflected light for $r_{in} = 0.5$, $N_{in} = 1$ and $Br = 1$ Gb/sec.
When \( r_n = 0.5 \), as shown in figures, 9, 10 and 11, \( t_{on} \) behaves as the same as figures, 6, 7 and 6 respectively but with a longitudinal peak around \( \phi = \pi \mod(2\pi) \) due to behavior of \( N_{on} \), which changes by the same way according to \( \beta \) (see eqn. (8a)). If \( r_n = r_s \), then \( N_{on} \) will be in the "undefined region" (not shown here) and corresponding to that we expect \( t_{on} \) to be in a critical or undefined value too.

### Table 1: Parameters values for SDL at room temperature (Nizette, M. and T. Erneux, 2004).

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<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
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<td>Radiative recombination coefficient</td>
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<td>m(^3)/sec</td>
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<td>Auger recombination coefficient</td>
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<td>( N_s )</td>
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<tr>
<td>( r_1,=r_2 )</td>
<td>Field reflectivities of the laser facets</td>
<td>0.566</td>
<td></td>
</tr>
<tr>
<td>( I_{inj} )</td>
<td>Injection current</td>
<td>( 2 I(T) )</td>
<td>A</td>
</tr>
</tbody>
</table>

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### REFERENCE


